A Proposal for Seedcorn Funds for UK Involvement in the T2K Experiment

S. Boyd, P. Dornan, K. Long,Y. Uchida, D.L.Wark*
A.N. Other (RG RA currently advertised)
Imperial College, London

I. Bertram, P. Ratoff
Lancaster University

R.Gamet, P.Sutcliffe,C.Touramanis
University of Liverpool

F. Di Lodovico, C. Williams
Queen Mary University of London

J. Butterworth, S. Canfer, C. Densham, R. Edgecock, J. Hirst, P. Loveredge, D. Morrow, G. Pearce, M.Woodward
Rutherford Appleton Laboratory

C. Booth, S. Cartwright, M. Navin, L. Thompson
University of Sheffield

J. Back, G. Barker, P. Harrison, A. Sheffield, A.N. Other (Physicist/Programmer post advertised)
University of Warwick

*To whom correspondence should be addressed, wark@imperial.ac.uk

Executive Summary

A combination of experiments worldwide have now demonstrated that neutrinos have mass and oscillate – the first confirmed evidence for physics beyond the Standard Model. Critical questions remain to be answered, however, with the measurement of the third mixing angle θ_{13} the next major target. A non-zero value for θ_{13} is a prerequisite for any terrestrial demonstration of CP violation in neutrino oscillations, which is the ultimate goal of oscillation physics (and the principle justification for building a Neutrino Factory). The T2K experiment, where the most intense artificial neutrino beam ever constructed will be produced at the newly built JPARC facility on Japan's east coast and directed underground to the refurbished Super-Kamiokande detector 295 km away, will represent a very substantial step forward in our ability to probe neutrino oscillations. Phase I of the experiment, with a 0.75 MW beam and Super-Kamiokande, will extend our sensitivity to θ_{13} by a factor of 20 over current limits. A proposed second phase of the experiment, with a 4 MW beam and a possibility of building a 1 megaton Hyper-Kamiokande experiment, would extend this sensitivity even further, and also (by comparing running with neutrinos and anti-neutrinos) begin to have sensitivity to CP violation if θ_{13} is not far below the existing limit. The T2K experiment has developed into a major international collaboration, with collaborators from at least 10 countries, fewer than half of whom are Japanese. The UK group is numerically the largest in Europe (where there are other groups in France, Spain, Italy, Switzerland, and interest in Germany). Dave Wark is the European Coordinator for T2K, and co-convenor of the EM/π^0 working group. The UK already has high visibility in the experiment, and it is growing.

The accuracy and reliability of the experiments depends crucially on a suite of near detectors which characterize the neutrino beam and its interactions before any oscillations take place. The UK group has obtained a major role in the specification, design, construction, and operation of the near detectors, and this proposal is the first request to PPARC to support this activity with seedcorn funding now to carry us through to the point in autumn 05 when a full proposal for construction of our part of the near detectors would be submitted. The bulk of the seedcorn funds would actually be support engineering and design of the neutrino beam line, in particular the target, target station, and beam dump. This activity cannot await a full proposal because of the aggressive schedule for the completion of the facility, and would in any case benefit the UK community through the experience in working on an actual high-power neutrino target.

1.1 Introduction - Neutrino Oscillations

The last 15 years have been an increasingly exciting time in the field of neutrino physics. Neutrino oscillations were shown to be the most likely explanation of the long-standing failure to observe the predicted flux of solar neutrinos when first the SAGE[1] and then the GALLEX[2] gallium radiochemical solar neutrino experiments reported a significant suppression of the observed flux of low-energy solar neutrinos. Neutrino flavour change was convincingly demonstrated by the SNO experiment[3], and then confirmed as oscillations by KamLAND[4]. Meanwhile observations of atmospheric neutrinos by Super-Kamiokande[5] (backed up by measurements by the Soudan II[6] and MACRO[7] experiments) showed a suppression of the atmospheric muon neutrino flux with zenith angle which was a perfect fit to oscillations, a finding confirmed by the K2K long-baseline experiment[8]. We thus have two confirmed observations of neutrino oscillations, thereby proving that neutrinos have mass. This is the first convincing demonstration of physics beyond the Standard Model, the implications of which are considerable. A third claim for neutrino oscillations by the LSND experiment[9] was not confirmed by the KARMEN experiment[10], which had similar sensitivity. In a minimal model with neutrino oscillations between the three known flavour states the LSND observation is inconsistent with the other experiments. It is currently being checked by the MiniBooNE experiment at Fermilab [11]. If against expectation the LSND result is confirmed by MiniBooNE, it would actually make the measurements planned in this proposal even more important, although we will not pursue this argument further here.

Neutrino oscillations may shed light on physics at scales beyond the reach of terrestrial accelerators[12], the mass they imply has implications for cosmology[13] and astrophysics[14], and the combination of these opens the exciting possibility of an explanation for the origin of the matter-anti-matter asymmetry in the universe[15]. A prerequisite for understanding these implications, however, is that we gain a thorough understanding of the phenomenon itself. A minimal neutrino oscillation model adds seven new parameters to the Standard Model – the masses of the three neutrino mass eigenstates, and the three mixing angles θ_{ij} and one CP violating phase δ of the MNSP mixing matrix[16]. The absolute masses have no effect on oscillations, as the actual observables are the differences of the squares of the masses Δm_{ij}^2. Vacuum oscillations do not depend on the sign of the mass differences, leaving an ambiguity in the ordering of the states which can only be resolved by observing matter effects (which do depend on the sign of the Δm_{ij}^2). Existing experiments have measured the angles θ_{12} and θ_{23}, the value of Δm_{23}^2, and the value and sign of Δm_{12}^2 (see Fig. 1). That leaves a number of unanswered questions still to be addressed[†]:

- What is the value of θ_{13}? So far we only have limits derived from the reactor experiments[17] at Chooz and Palo Verde, from solar neutrino experiments, and from Super K – $\sin^2\theta_{13} < \sim 0.14$.
- Is $\theta_{23} = \pi/4$, i.e., is 2-3 mixing maximal? We currently know that $\sin^2\theta_{23} > \sim 0.9$, and more precision is crucial in constraining neutrino mass models.
- What is the sign of Δm_{23}^2 (or Δm_{13}^2) , which is also of great interest to model builders?
- Is there CP violation in neutrino oscillations, i.e., is $\sin\delta \neq 0$?

[†] Of course there are other critical questions in neutrino physics (are neutrinos their own anti-particles, and what are the absolute neutrino masses?), but these cannot be addressed in oscillation experiments.

2.0 The T2K Experiment

A combination of existing and planned facilities in Japan offer an almost ideal fit to the needs of a next generation neutrino oscillation experiment looking for sub-leading $\nu_\mu \rightarrow \nu_e$ oscillations. The JPARC facility, being built at Tokai on Japan's east coast, is a joint project of the Japanese Atomic Energy Research Institute (JAERI) and KEK, originally intended primarily for neutron scattering and high-energy nuclear physics. The presence of a high-power 50 GeV proton synchrotron (PS), however, led to the idea of producing an intense ν_μ beam aimed at the Super-Kamiokande detector by the conventional technique of producing charged pions by colliding the proton beam with a target and collecting and focussing the pions (selecting one charge, usually positive, in the process) into a decay volume. The resulting decays produce beams of ν_μ and muons, and the decay volume length is adjusted so that most of the pions but as few of the muons as possible decay before they reach the beam dump at the end. This experiment (now called T2K) has a number of major advantages in the search for sub-leading oscillations:

- Any measurement of sub-leading oscillations needs the maximum possible flux to maximize the statistical sensitivity. To first order the neutrino flux depends on the beam power, and the JPARC beam will be the highest-power pulsed proton beam ever built. In Phase I the design calls for 0.75 MW of protons on target, while a Phase II upgrade is planned to 4 MW after ~5 years.
- Given the known oscillations parameters and the distance from JPARC to SuperK (295 km), the first oscillation maximum will be for neutrinos with energies of about 600-800 MeV, right at the maximum of the cross-section for the quasi-elastic reactions that permit accurate determination of the neutrino energy (needed for the precise measurement of θ_{23} and Δm_{23}^2.
- This advantage will be enhanced by using an off-axis beam geometry[18], which gives a higher flux at the oscillation maximum, a more sharply-peaked neutrino energy spectrum, and a smaller intrinsic beam ν_e contamination.
- The far detector, Super-Kamiokande, is almost ideal for this measurement, which requires a large, well understood detector which can cleanly distinguish the signal ν_μ's, ν_e's, and background π^0's produced by neutral current interactions. SuperK is (and will be for some time) the world's largest underground detector, and has been the subject of intense study for many years and thus has very well understood energy resolution, and offers excellent and well-understood particle id capabilities for the low-multiplicity events at these energies. Of course another major advantage is that the experiment already exists and will be fully operational (with the full complement of phototubes replaced) well before the turn-on date for the T2K beam.
- An extensive suite of near detectors will be used to fully characterise the beam in Tokai, thereby minimizing the systematic uncertainties in measuring ν_μ disappearance and permitting very accurate determination of the oscillation parameters, while at the same time enabling an absolutely convincing quantification of the ν_e background expected at SuperK, allowing any excess seen to be confidently attributed to oscillations.

These advantages have led to the formation of a major international collaboration to build the T2K experiment. At the time of the last LoI the collaboration (see bibliography) had 145 signatories from 10 countries, 46 of these from Japan, and since the foreign group has grown. The project has been approved in Japan, with a total budget of ~165$M which covers all civil construction costs and most of the capital costs of the beamline, target, decay volume and beam dump (see detailed description below). Foreign contributions will be necessary to provide the near detectors, and to supply additional engineering, design expertise, and some components in the beam complex if the experiment is to accomplish its ambitious sensitivity goals. Let us now consider the experiment in more detail before outlining the proposed UK contributions.

2.1 The Beamline

Due to space constraints on the JPARC site, the proton beamline for the T2K beam has to be bent in a tight radius inside the 50 GeV ring (see Fig 1). This requires the use of dual-function (dipole and quadrupole) superconducting magnets that are currently under construction at KEK. Beam losses must be maintained at less than 1 W/m in the superconducting section, which produces challenges for beam monitoring and halo. The UK has provided some advice on the proton monitors based on the experience at ISIS, however given limited manpower we do not propose to pursue this further despite the fact that it would be of great benefit to the project.

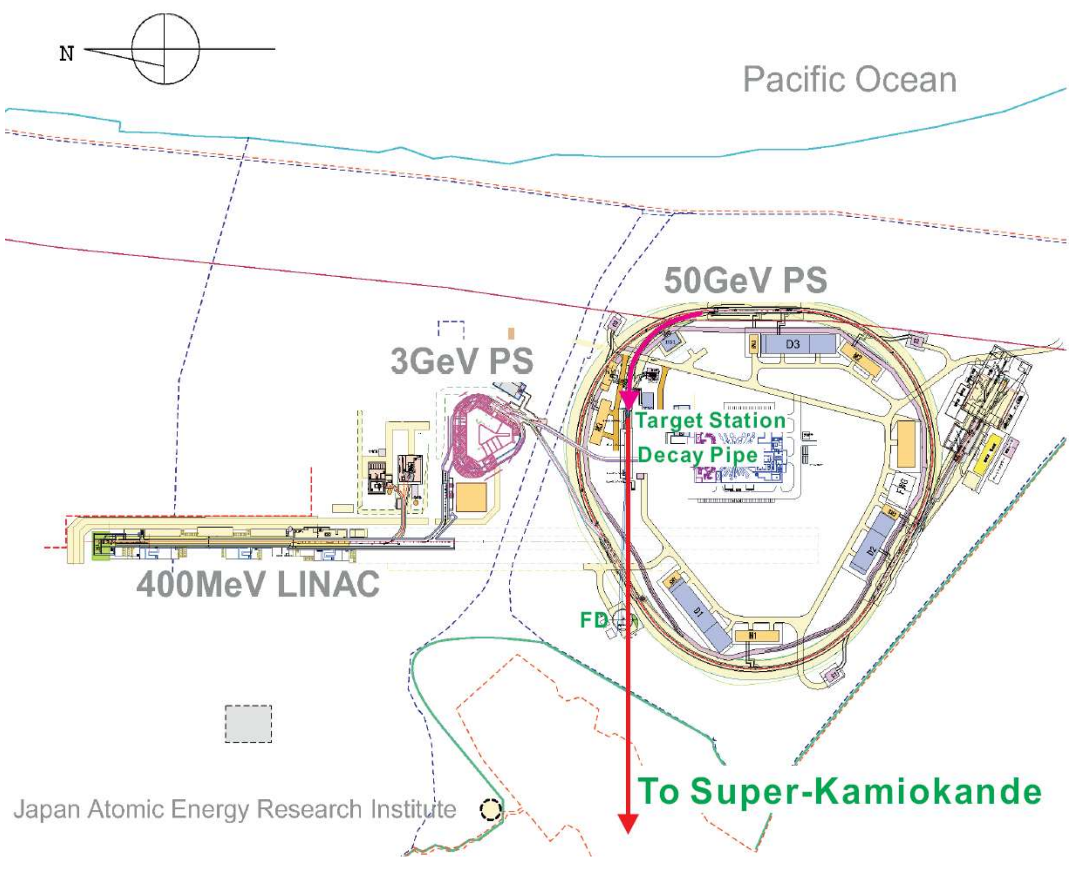


Figure 1. The overall layout of the T2K beamline. The proton beam is extracted in a single turn and bent inside the 50 GeV ring where it hits a pion production target. The resulting pions are focussed into a decay volume to produce the neutrino beam.

2.2 The Target and Horns

The first step in the conversion of the proton beam into a neutrino beam is the collision of the proton beam with the pion production target. The resulting pions are collected and focused forward into the decay region by a magnetic horn system. In order to maximize collection efficiency the target is actually located inside the first horn. The target/horn system is almost certainly the most technically challenging part of the project. To get a feel for the difficulties, note that if single pulse of the 0.75 MW beam hit a solid iron block it would raise the internal temperature of the block to 1100° C and produce stresses exceeding the tensile strength of the material. The target must survive such pulses every 3.64 seconds for roughly 1/3 of the year without failing, it must have very little material around it so that the pions can escape and be efficiently collected, and it must not interfere with the horn magnet which surrounds it. Of course the targets and horns will become very heavily activated within a very short time of the beginning of operation, so any maintenance/repair activities will have to be conducted remotely, and any damaged/discarded targets will have to be stored as high-level waste. A conceptual design for a graphite rod target is shown in Fig. 2. The target is cooled by high-flow He gas contained within the thin-walled surrounding vessel. Detailed engineering is critically needed both on the target itself and of the target station (see Fig 2).

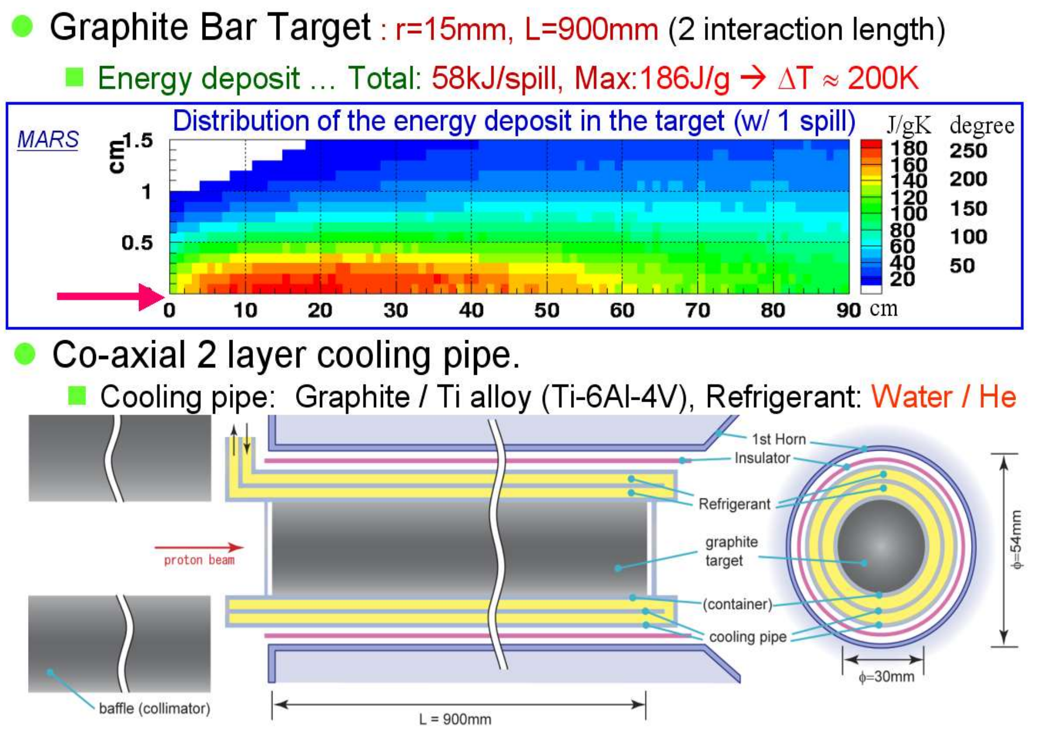


Figure 2. Conceptual design of target

2.3 The Decay Volume and Beam Dump

The pions exit the horns into a ~110m long He-filled decay volume where the neutrinos are produced. At the end of this decay volume is the beam dump, where any undecayed pions as well as the remaining proton beam are stopped (this amounts to about ¼ of the total initial proton beam power). Although this is not the most technically complicated part of the facility, there are a number of factors that complicate the design. To minimize expense the beam dump must be made as short as possible, and the thickness is also constrained by the need to keep the energy loss of muons traversing the beam dump as low as possible (so that the beam direction can be determined from monitoring the low-energy muons from pion decay). In order to minimize the amount of highly-activated water that needs to be disposed of the dump is cooled only from the sides. However the main problem is that no provision exists for access to the dump after construction is finished, so it must be built to withstand the full 4 MW beam power, and it must not fail for the 25 year life of the facility.

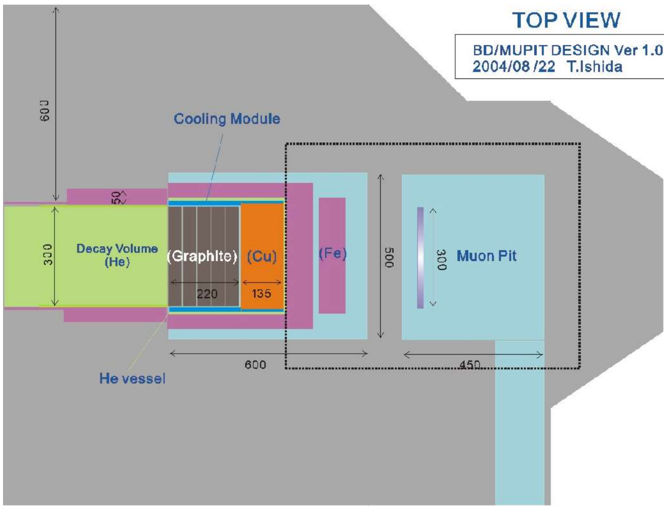


Figure 3 Top View of Beam Dump/Muon Pit

A top view of the current beam dump design is shown in Fig 3. The core consists of a graphite front plug, followed by Cu and Fe to range out all the hadronic secondaries. This is followed by meter of concrete to complete the biological shielding of the muon monitor room. The muon monitors are quite a challenge in themselves, as they determine the shape of the muon beam profile to an accuracy of a few percent while withstanding $2.4\text{x}10^{14}$ muons/cm^2/yr. Given the large area a sparse array of detectors will be used, but the exact technology and, most importantly, the method of establishing and maintaining the relative normalization of these detectors at the few percent level, is yet to be worked out. The UK have been approached about the possibility of supplying rad-hard electronics if diamond detectors are used, so there is a chance that we will be asking for some funds for this in our full proposal (although we are not asking for anything at this point).

2.4 The Near Detectors

Fig. 4 shows the neutrino spectrum as a function of the angle between the beam centre and the detector, and the neutrino charged-current cross-sections. This shows the advantage of an off-axis beam – the resulting neutrino beam is peaked sharply at the energy where the charged-current quasi-elastic (ccQE) cross-section is a maximum. QE events produce a single visible muon in the final state (along with a low-energy recoil proton), which permits the accurate reconstruction of the neutrino energy (which is necessary for a precise measurement of θ_{23} and Δm_{23}^2 in the disappearance channel). The critical measurement of $\nu_\mu \rightarrow \nu_e$ appearance also benefits from the off-axis geometry, as the large high-energy tail visible in the 0º beam in Fig. 3 is the source of neutral-current (NC) produced π^0's, which can be mistaken for the single electrons produced by ccQE events from ν_e (which are the signal for ν_e appearance). Furthermore the off-axis beam has a smaller intrinsic ν_e contamination arising from kaon and muon decay than an on-axis beam (the flux ratio of ν_μ/ν_e is approximately 250 at the peak energy for the 2.5º beam which will be used

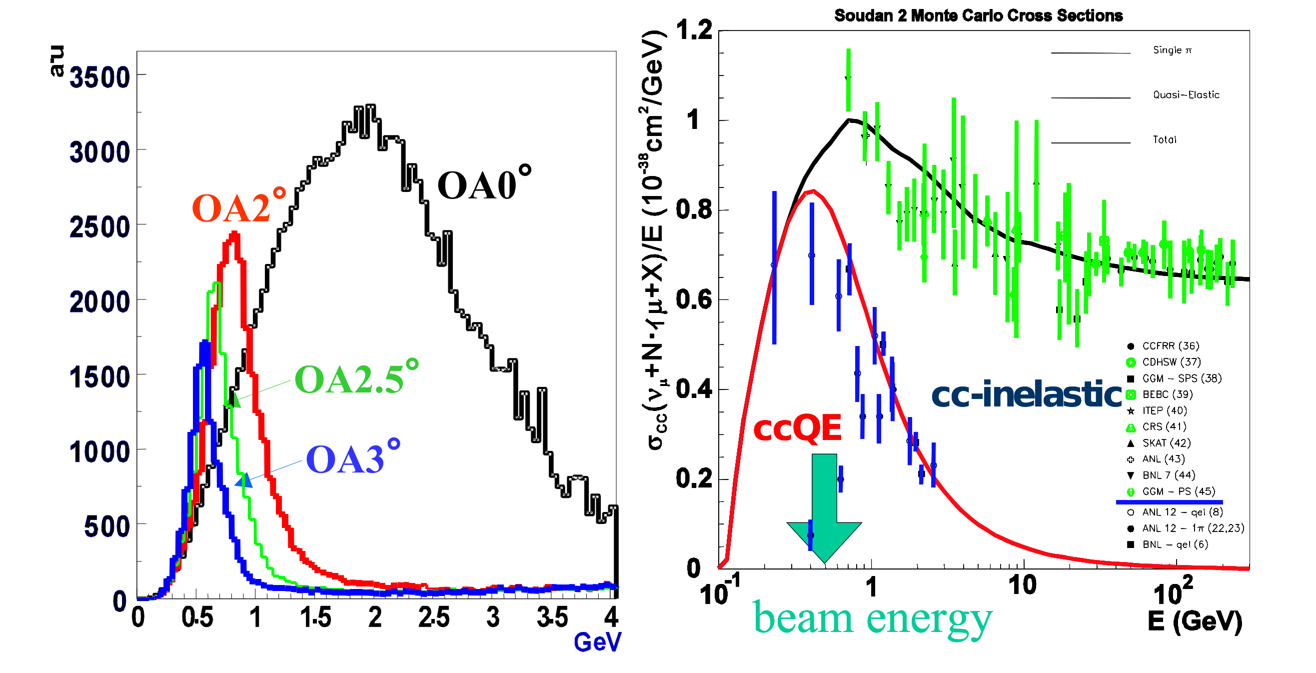


Figure 4 Neutrino energy spectrum as a function of off-axis angle and the charged-current (CC) cross-sections for quasi-elastic (QE) and inelastic reactions.

in T2K). Even with these advantages, however, the detailed understanding of the beam properties is still one of the most critical issues in the experiment. This will be accomplished using a suite of near detectors located 280m after the target (i.e., 150m downstream of the dump after all the muons from the beam have been ranged out by passage through the ground).

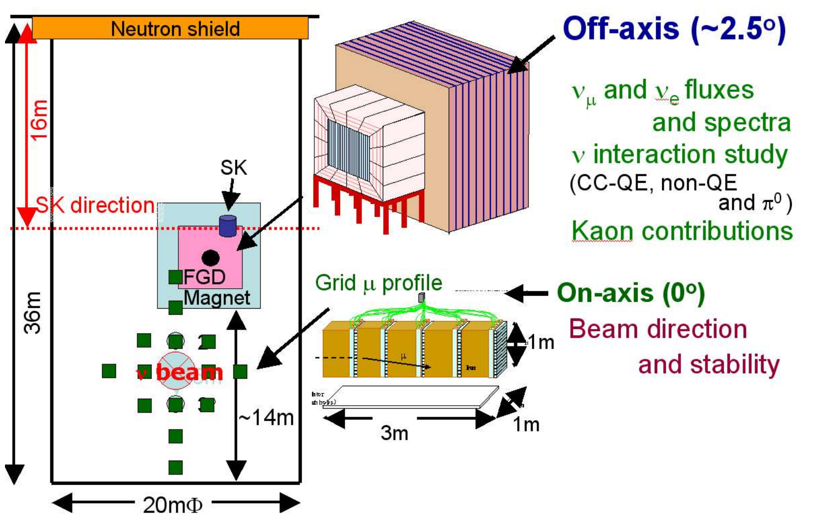
1. 

Figure 5 280m Detector Overview

The 280m on-axis – This detector, or rather these detectors, will be a grid of very simple iron/scintillator sandwiches to measure the neutrino beam direction and profile. These detectors are important because the price that you pay for the benefits of an off-axis geometry is that the properties of the beam become a strong function of its direction and divergence, and these must therefore be monitored closely.
2. The 280m off-axis – This detector, or rather system of detectors, is intended to be the main focus of UK efforts in the initial phases of T2K, and therefore

more details will be given below. For the ν_μ disappearance experiment the main issues are the flux and energy spectrum of the beam ν_μ, and an understanding of the interactions of the high-energy neutrino tail which will feed events down in energy into the oscillation energy region in Super-Kamiokande (of course the best way to get rid of such events is to get rid of the high-energy tail, which is one of the main reasons for the off-axis geometry). For the ν_e appearance experiment the key issues are the intrinsic contamination of the beam with ν_e's from kaon and muon decay, and the rate of production of single π^0's by NC interactions of the beam (which has mostly oscillated to ν_τ by the time it reaches Super-Kamiokande, and hence is below threshold for CC interactions). A major recent development is the acceptance by the collaboration of the European proposal to magnetize the 280m detector by embedding it within the old UA1/NOMAD magnet, which CERN has kindly agreed to donate/loan to the collaboration. The presence of a magnetic field will improve the momentum determination for QE muons, allow charge identification for many tracks, separate the conversions from the two photons from a π^0 decay, and a number of other advantages which are still under study.

3. The 2km detector – This detector is an attempt to get around the major drawback of the off-axis geometry. From only 280m away the decay region does not appear as a point, but as a line, and a range of angles from that line intercept the near detector. By the time the neutrinos get to Super-Kamiokande, however, only a tiny angular range is accepted. Thus there is an acceptance correction between the near and far detectors which is not small (see Fig 6). In the initial phases of the experiment (where uncertainties will be dominated by statistics) this should not be a problem, but in order to reach the ultimate systematic sensitivity for both the appearance and disappearance experiments (and for demonstrating convincingly that any appearance signal seen really does arise from oscillations) it would be best to avoid this correction. That is the purpose of the proposed near detector complex 2 km from the target. At that distance the beamline acceptance already looks essentially the same as it does at Super-Kamiokande, so it would provide quantitative proof of the acceptance correction from 280m. The current thinking is to place a ~2 kt water Cerenkov detector there, coupled with some fine-grained detector (perhaps a liquid argon calorimeter) to make detailed measurements of neutrino interactions. An appropriate site owned by Tokai village has been identified and permission for its use secured, but unfortunately there are insufficient funds in the budget for the civil construction of the detector hall during the initial phases of the project. The 2km detector will therefore be built as an upgrade to the experiment at a later date.

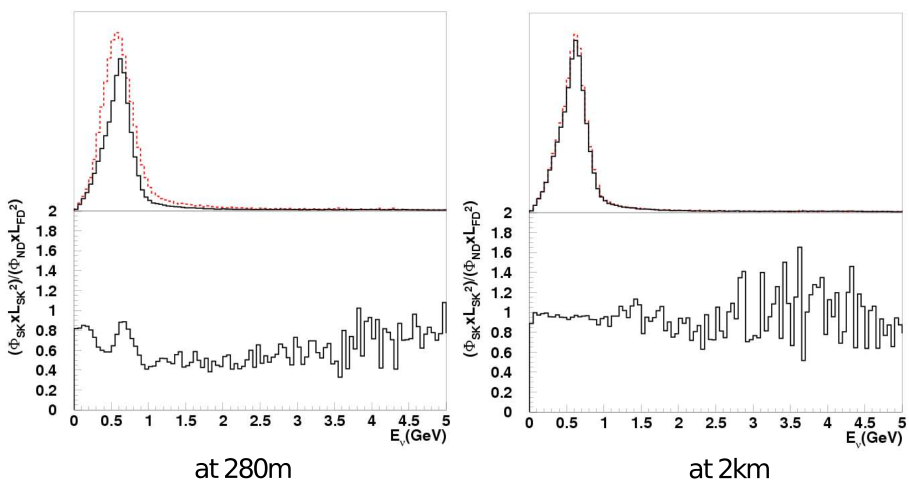


Figure 6 Near/Far ratio at 280m and 2km. The red curves at the top are the spectrum at Super K, the black curves are the spectra at the given distances, and the bottom curves the ratio.

2.5 Super-Kamiokande

The Super-Kamiokande detector has been successfully operated for atmospheric and solar neutrinos since 1996. In the energy range of interest the detector has a well-understood response to electrons, muons, and pions, and will be further studied and optimized as part of this programme. The chain-reaction implosion of several thousand of the phototubes in November 2001 has been widely reported, and resulted in the detector being rebuilt with the surviving tubes and correspondingly reduced sensitivity. New phototubes have now been built and will be installed beginning in October 2005, to be completed by 2006. All phototubes will be individually protected in acrylic/fibreglass enclosures that will prevent the repeat of any chain reaction. The UK group will probably wish to participate in the rebuilding, which will require some travel funding.

2.6 Expected Physics Sensitivity

Given that the T2K experiment is almost ideally suited for the study of $\nu_\mu \rightarrow \nu_e$ appearance, having the most intense beam, the proper energy and baseline, a large, well-understood far detector with excellent capability to differentiate signal from background, and the most extensive suite of near detectors for the detailed characterization of the beam so far proposed, what sensitivity will it provide? As with any proposed experiment this is not an easy question to answer. In particular the work which the UK group is currently pursuing (which will be described below) is intended to produce a better understanding of the impact of the near detector measurements on the systematic uncertainties in the measurements at Super- Kamiokande, and the results of this study are not yet available (although they will be before a proposal is submitted for the full construction budget). However we will offer a preliminary estimate of sensitivity at this point so that the value of the project can be assessed.

Fig 7 shows the expected measured muon energy spectrum in Super-Kamiokande. The ν_μ disappearance measurement consists of looking for the dip in the spectrum caused by oscillations, as shown in the centre and right hand panels (note the very different vertical scales, showing that due to the optimal selection of energy and baseline, most of the neutrinos have oscillated away). In principle the measurement of the depth of the dip gives the value of $\sin^2 2\theta_{23}$, and its position gives Δm_{23}^2. In practice both measurements are complicated by the presence of non-QE events from higher-energy neutrinos (shown in cross hatch in the plots), and a precise understanding of these events is one of the principal reasons to build the near detectors. Our preliminary estimate is that we will have systematic uncertainties of 5% in the normalization and non-QE/QE ratio, 1% on the energy scale, 20% on the spectral shape and 5% on the spectral width. These would allow us a measurement accuracy of $\delta(\sin^2 2\theta_{23}) \sim 0.01$ (about an order of magnitude better than will be achieved by MINOS) and $\delta(\Delta m_{23}^2) < 1 \times 10^{-4}$ eV^2, which is also about an order of magnitude improvement on what is expected from MINOS, in 5 yrs, assuming 10^7 seconds of running per year at nominal intensity.

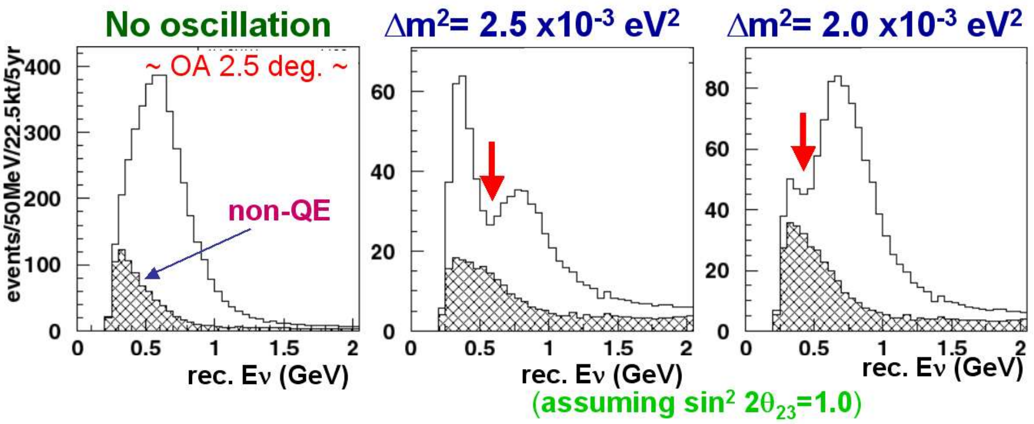


Figure 7 Muon neutrino spectra observed at Super K for various oscillation parameters.

The signal for the $\nu_\mu \rightarrow \nu_e$ appearance search are ν_e QE events in Super- Kamiokande, and the backgrounds arise primarily from the intrinsic ν_e contamination in the beam, and from mis-reconstructed π^0's arising from NC interactions of the beam. These are precisely the targets of the the 280m ECAL which is currently the subject of intense study within the UK. Any numbers given here are very preliminary. Detailed studies have been made of the ability to reject beam ν_e (which have a very different energy spectrum to signal ν_e) and π^0's in Super-Kamiokande, what is less well known is the expected level of these backgrounds from our beam. These preliminary studies would imply that in 5 yrs of running we could expect to see 122±3 signal events for Δm^2=2.5x10^{-3} eV^2 (the current best fit), $\sin^2 2\theta_{13} = 0.1$ (just below the current limit), while the backgrounds primarily from π^0's would be 12±0.8 and the background from beam ν_e would be 16±0.4 events (where the uncertainties in all these numbers are the statistical errors from the number of events simulated, systematic errors are thought to be smaller than the statistical errors one would expect, but this is still be worked on). The expected signal and background for the above parameters is shown in Fig 8, which also shows the sensitivity to $\sin^2 2\theta_{13}$ as a function of the uncertainty in the backgrounds eventually achieved and the exposure. Shown in the latter plots are two lines to indicate the goal of the first phase of T2K, and an eventual goal that could be reached by the Phase II intensity upgrade of JPARC to 4MW and the construction of a 1 megatonne Hyper-Kamiokande detector.

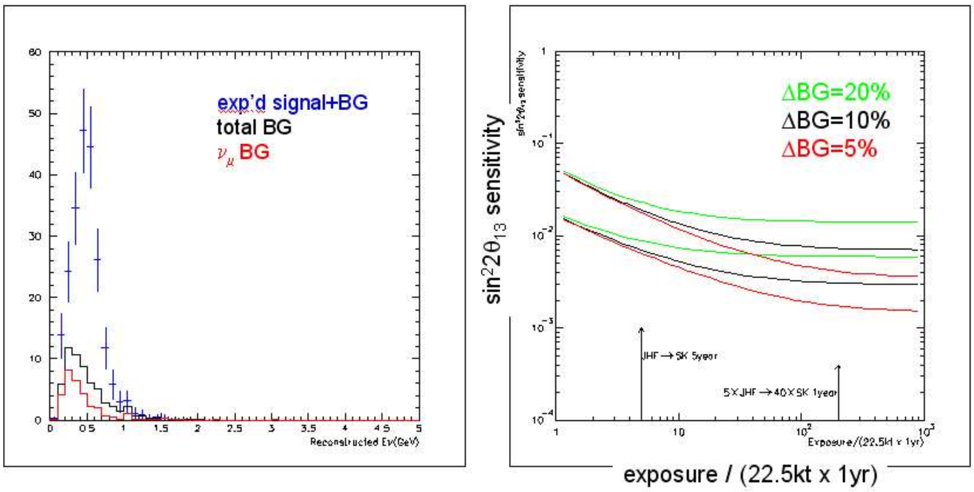


Figure 8 Signals and backgrounds for $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{13} = 0.1$, and on the right the eventual $\sin^2 2\theta_{13}$ sensitivity as a function of exposure for various background uncertainties.

3.0 Competing Projects

Long baseline neutrino oscillation experiments which are already under construction should produce a modest improvement in our sensitivity to θ_{13} within the next 5 years. The MINOS experiment using the NuMI beam at Fermilab is optimised for the observation of muon neutrino disappearance and was designed before the value of Δm_{23}^2 was well-constrained (and when it was, in fact, thought to be substantially larger than the current allowed range). MINOS is therefore on-axis, in a higher-energy beam, and with a relatively coarse iron sampling calorimeter. These factors unfortunately limit the experiment's sensitivity to ν_e appearance, although it is expected to improve on the Chooz sensitivity by about a factor of two after five years of running. The OPERA experiment at Gran Sasso, using the CNGS beam from CERN, is optimised for the observation of ν_τ appearance using a large hybrid emulsion detector. The CNGS beam is therefore at even higher energy than the NuMI beam, the baseline is too short for full oscillations to develop, and perhaps most critically, there is no near detector and therefore any statements about backgrounds from inherent contamination in the beam will be based solely on Monte Carlo. They claim a similar factor of two improvement in sensitivity from 5 years running at nominal flux (which will take them well past the scheduled turn-on of T2K). The ICARUS experiment, which is planned for Gran Sasso as well, will make similar measurements to OPERA but using a magnificent liquid argon TPC which gives bubble-chamber quality imaging of events (however they suffer the same drawbacks mentioned above for OPERA, in particular, the lack of a near detector). They claim a factor of 5 improvement over the Chooz limit, however on current schedules their full detector would not be installed until at least 2008, and therefore it is not clear (given the much greater rates at T2K and therefore shorter time to the same statistics) that they will compete with T2K.

There are a number of other planned neutrino oscillation experiments, two of which are potential competitors on the time scale of T2K for physics results (and for UK involvement). The first of these is a proposal to build a detector – called NOvA – on the surface in northern Minnesota as an off-axis detector on the NuMI beam. The current design calls for a 50 kton low-Z tracking calorimeter based on the scintillator technology designed for MINOS. The sensitivity to θ_{13} is designed to be similar to T2K, however the longer baseline and higher energy opens the possibility of observing matter effects. The other potential competition comes from proposals to build new experiments to observe electron anti-neutrino disappearance from reactors. As mentioned above the best existing limits on θ_{13} come from reactor experiments, and the idea of the new experiments is to compare measurements at two reactors, one close enough to the reactors to act as a measurement of the unoscillated flux/spectrum, and then a more distant detector which measures the rate changes and spectral distortions caused by oscillations. The oscillations are dominated by the solar parameters but, as in the case of accelerator neutrinos, there is a subleading contribution driven by θ_{13}. One such experiment (without UK involvement) has already been approved at the Chooz reactor. A UK group has expressed interest in an experiment at the Braidwood reactor in Illinois. Although the exact reach in θ_{13} depends on the eventual systematics achieved in the comparison of the two detectors (the effect being sought is at the percent level, so systematics must be at least similar), it is currently estimated to be similar to the reach of T2K.

So why are the UK T2K collaborators asking to join T2K rather than one of the other experiments? There are many reasons:

- The T2K experiment is fascinating physics, and we have succeeded in carving out a clear and significant role for ourselves within the programme which will guarantee that the UK makes a real and visible contribution. The 280m detector is critical to the physics, but has almost no Japanese participation.
- The 2km detector would give T2K the ability to demonstrate ν_e appearance in a far more convincing manner than alternative experiments, and it should also give T2K the ability to make better measurements of ν_μ disappearance. It is worth remembering that KamLAND was the third reactor experiment to claim evidence for oscillations (the first two were spurious), and there have been at least two accelerator experiments that found oscillations that weren't there (assuming LSND is wrong). The 2km detector acts as a null experiment for T2K, making the experiment very hard to fool. Even without the 2km detector the combination of the extensive measurement programme at 280m and the well-understood Super-Kamiokande detector allows T2K to perform multiple checks of any claim. It appears very likely that T2K will be first, but even if not, in the long run it seems that it will be the best of the currently proposed experiments.
- With respect to the NOvA programme, the main difference to be blunt is that T2K is being built and NOvA is being talked about. The status of NOvA within the US funding system is not clear, and its cost (~$150M, or almost as much as the entire T2K programme) will mean that approval is unlikely to be rapid. However even in the absence of such considerations, the physics advantages of T2K (the low energy, high intensity beam, and excellent detector) would still give it the edge.
- The sensitivity of the double-Chooz experiment is much less than T2K, and its reliance on rate differences at the two detectors seems unlikely to yield a compelling measurement of θ_{13}.
- The other reactor experiments suffer from similar uncertainties concerning schedules and funding to NOvA. Although the cost for a two-detector reactor experiment is smaller than NOvA, it is still not negligible and therefore must pass through the usual stages of the US funding process before serious

engineering or civil construction can begin. It therefore seems unlikely to be faster than T2K.

- While the reactor experiments are claimed to have similar sensitivity to T2K for θ_{13}, their low-energy and isotropic source makes them unsuitable for looking for matter effects (and thus the sign of Δm_{13}^{2})), and they cannot even in principle see CP violation (there is no CP violation in a disappearance channel). The physics seems to naturally direct the long-term future of neutrino physics in the direction of longer baselines and higher intensity beams culminating in a Neutrino Factory, and T2K is a natural part of this progression in a way that reactor experiments are not. Working on T2K therefore puts the UK community in a better position for the next stage.
- The Japanese have an aggressive plan for future development of T2K, including a 4 MW upgrade for JPARC and the possibility of building a 1 mega-ton upgrade of Super-Kamiokande called HyperK. Such an experiment begins to have useful sensitivity to CP violation (for large values of θ_{13}), and would therefore be an excellent physics opportunity. There is a similarly ambitious plan to develop the JPARC facility in stages to a Neutrino Factory based on fixed-field alternating gradient synchrotrons (FFAG's). While the technical feasibility of this is not proven, it is by no means disproven, and the Japanese have an excellent track record of delivering neutrino projects. If this programme is realized the UK could greatly benefit from being involved at an early stage. If the Neutrino Factory is not built in Japan the experience gained on T2K, in particular on the targetry and on the detailed understanding of neutrino interactions, would benefit the UK community wherever else the Neutrino Factory is built.

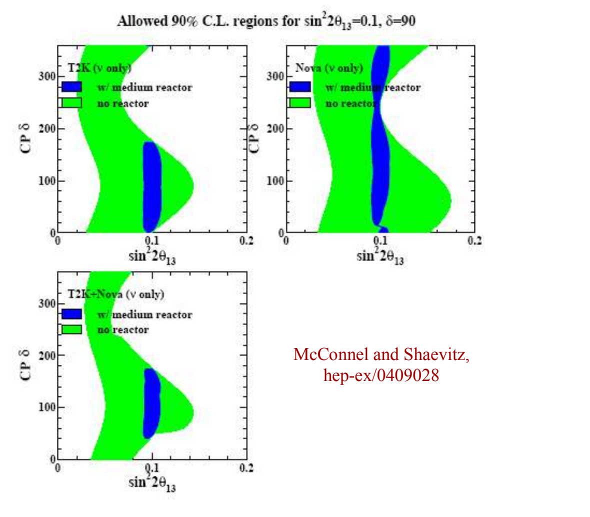


Figure 9 The power of combining experiments. The green regions show allowed regions from T2K, NOvA, or the combinations, the blue add information from a proposed reactor experiment.

All this explains why, given that one can only work on one of these experiments, that T2K is our choice. However, from a more global point of view, one should strongly point out that T2K, NOvA, and a two-reactor experiment designed to see spectral distortions, are not really competing experiments, rather they are strongly complimentary. The reason is that, while each experiment makes one or two measurements of oscillations (disappearance and, for the accelerator experiments, appearance), the oscillation probabilities depend on 3 angles, 3 mass-squared differences and their signs (through matter effects), and the CP phase. Even if some of these parameters are fixed by other experiments, such as solar neutrino experiments and KamLAND, each individual experiment still tends to be underconstrained. There is a huge literature on the correlations between the parameters and on degenerate solutions[19], and emphasizing the importance of multiple experiments to help point to a unique solution (see Fig 9). We therefore would support all the experiments, however we would emphasize that the UK should commit to making a substantial impact on at least one, and therefore we would hope that sufficient resources be made available to the UK T2K collaboration to make sure that we can be major players in the T2K experiment.

4.0 Proposed UK Contributions.

The Super-Kamiokande experiment already exists, so beyond some manpower to assist in its rebuilding, no major contribution to the far detector is anticipated during the construction phase (although the UK, through the SNO experiment, has considerable experience in the calibration and analysis of data from water Cerenkov detectors that will be very useful during the analysis phase). That leaves two major areas where contributions could be made – the neutrino beam facility itself and the near detectors. The UK group proposes to make significant contributions to both. The particle physicists will concentrate on the specification, design, construction, calibration and operation of the 280m near detector, with a particular concentration on the electromagnetic calorimeter. Meanwhile the accelerator physicists, designers and engineers at RAL (primarily in EID) will make significant contributions to the design and engineering of the target, target station, and beam dump. Other, smaller contributions are also being considered and may be added to the full proposal. At a later time a supplemental proposal will be submitted for the 2km detector, and the UK collaboration plans to play a significant role in those detectors as well. The following sections discuss the proposed contributions in more detail.

4.1 The 280meter detector

The current baseline design for the 280m detector showing the major elements is sketched in Fig 10. Working from the outside the detector is surrounded by the UA1/NOMAD magnet, which establishes a 0.2T magnetic field and also acts as a side MRD (muon range detector) as the magnet has internal slots which we propose to instrument with plastic scintillator. Inside the magnet is the electromagnetic calorimeter, or ECAL. We have not yet finalized a technology or design, but are currently working on the assumption that this will be a Pb/scint tracking calorimeter. Inside the ECAL are two separate areas, a front area (called the π^0 detector, or pod) which contains a large fine-grained 100% active tracking calorimeter (FGD) made of strips of plastic scintillator. The back section consists of one or more additional FGD's surrounded by high-resolution tracking detectors (currently planned to be TPC's). Downstream is a muon identifier, while upstream there may be an active veto (not shown on this drawing). The two sections have slightly different goals. The front section is optimized for the measurement of electromagnetic events – primarily either ν_e ccQE events, or NC π^0 production. The back section is intended for the accurate measurement of ν_μ ccQE events to establish the flux and spectrum for the ν_μ disappearance measurement.

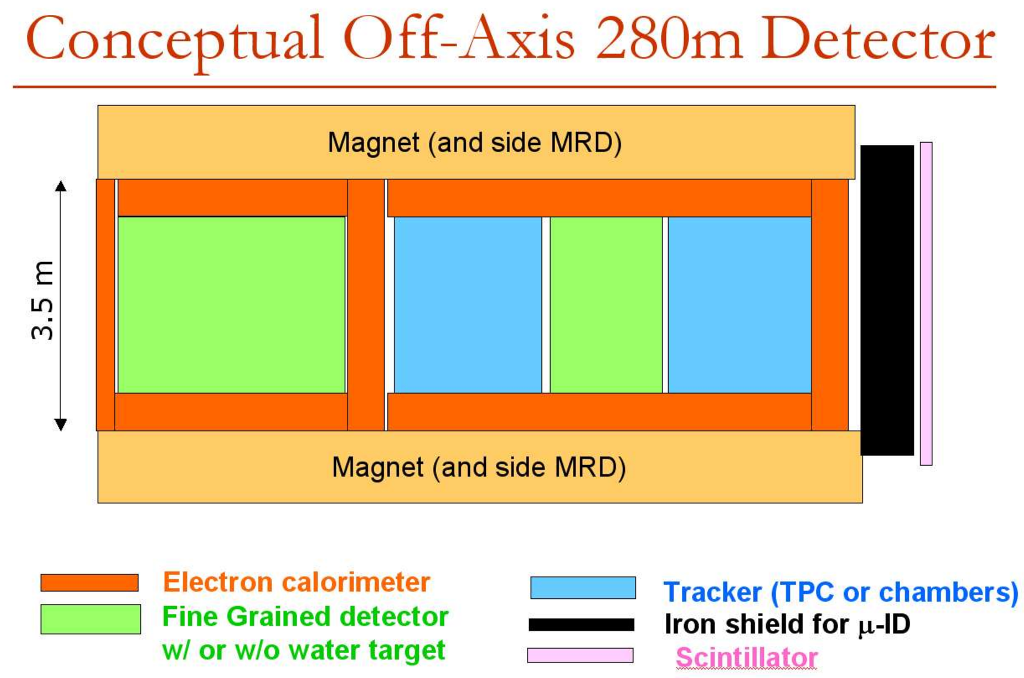


Figure 10 Block layout of the elements of the 280m off-axis detector.

There continues to be a considerable amount of work within the collaboration on the optimal design of this detector, in particular, on the size and placement of the ECAL. Alternate designs exist with the ECAL missing its downstream section, the transverse section in the middle, and even with the ECAL integrated into the FGD in a manner similar to that proposed for the MINERvA experiment at Fermilab[20]. The UK group (primarily Uchida and Boyd at Imperial, Di Lodovico at QMUL, and Barker at Warwick) are engaged in an intense Monte Carlo exercise using code written by the UK group based on code previously used for MINERvA (and even for NOMAD). This simulation includes a nearly complete geometry for several proposed detector configurations, and for complex elements such as the magnet, and is by far the most detailed simulation of the detector now available to the collaboration. This demonstrates that the UK group has gone from zero to leading this activity in T2K in the period of only a few months. Fig. 11 shows two simulated events in the pod. The one on the left is a ν_e ccQE, the one on the right a NC π^0. This demonstrates the importance of the ECAL, as the two events would be difficult to distinguish if the soft γ seen in the downstream segment of the ECAL on the right were missed (of course the presence of the recoil proton, not visible at this scale but visible in the FGD, also helps distinguish these event classes). The UK group is also the only group in the collaboration currently engaged in the complex task of simulating all the potential beam-related backgrounds, an essential issue for detector design as it may have a strong effect on the desirability of a hermetic calorimeter not just to keep events from leaking out, but also to keep them from leaking in (a few preliminary numbers for those who think that pileup cannot possibly be a problem in a neutrino beam, we calculate that there will be ~1400 events per spill within a 3m shell around the 280m pit, 4-5 of which will make muons that will penetrate and produce a hit in the FGD within the pod, in addition there will be 46 events/spill in the magnet iron. These should be compared to the signal rate of about 0.5 events/spill in the pod FGD – obviously good timing will be necessary to separate out these background events).

A second problem with the 280m detector is that the design shown is made out of plastic, or lead, or iron – in other words, no water. The far detector, of course, is water, and the current theoretical understanding of the corrections for the cross section

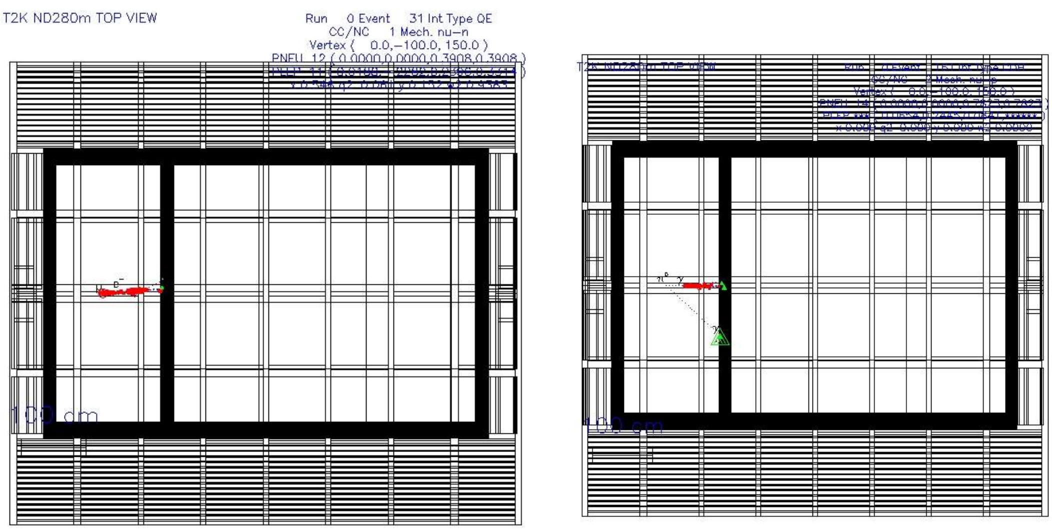


Figure 11 Two events (ν_e ccQE on the left, π^0 on the right) simulated with SteveMC, the UK T2K group's 280m simulation package.

differences from one nucleus to the next (especially the modifications for pion absorption in the nuclear medium which can make 30-50% corrections to the cross-sections) is rather poor. For this reason the collaboration believes that there should be a water target as part of the forward pod FGD, and it would be most desirable (or even essential, this is another topic for current simulations) if this target were active. The Sheffield group has considerable experience in the design and testing of new scintillators based on their work in the UKDMC collaboration, and we propose to put this experience to good use within T2K by collaborating with the Canadian groups that are currently working to design an active water target. The Sheffield group will put a graduate student on this task (Marieke Navin), and requests some small equipment items to help in tests of water-based scintillators (see below for numbers).

The current plan calls for a meeting in Rome in early December when the design parameters of the 280m detector will be fixed. From there we must write a TDR, and the plan is that this will exist (at least in nearly-final form) by March. This would form the basis for a full proposal to PPARC next autumn. The current UK thinking, if the detector design does not undergo too great a change between now and the TDR, is that we would bid to supply the complete ECAL with all elements including scintillators, optical sensors, electronics, and DAQ code (the last being possibly a route to supplying the DAQ code for the entire 280m detector based on RAL experience with MINOS). At this point, with the size, configuration, and technology for the 280m as of yet unspecified it is impossible to give anything other than a notional figure for its cost, but comparing to similar systems elsewhere suggests a cost of order £2-4M including manpower. We are not currently seeking any of this, however, as what we currently need is time to complete our simulation studies to determine the optimal detector design. For this we are only requesting travel money (see below). We have also agreed, as part of the European T2K commitment to supply the UA1 magnet and ancillary equipment to the experiment, that we shall approach PPARC as part of the full proposal for funds for our "share" of the costs of supplying the magnet (shipping, power supplies, etc.). The exact cost is not known, but is estimated to be about 700 kilo-euro, of which our share is yet to be negotiated but might be, say, 100-150 k£.

4.3 The 2km Detector

As noted above, there is insufficient money in the Japanese civil construction budget to supply the hall for the 2km detector during initial construction of the experiment. However the 2km detector remains highly desirable, as it appears necessary for the experiment to reach its ultimate systematic sensitivity and to produce an absolutely convincing demonstration of ν_e appearance. It thus appears that the 2km detector will be delayed until a later stage of the experiment. This is unfortunate, because of course it means that once the 2km detector is completed the experiment will have to run again for a period of years to get a statistically significant data set in the 2km detector. One possibility would be for the foreign collaborators to find sufficient resources not just to build the 2km detector itself, but the detector hall and its excavation as well (a sum estimated at ~12m$). We are not currently asking PPARC for a contribution to this sum, but if an amount of approximately £6M could be found on the time scale of 2008-2010 it would open up interesting possibilities of getting the rest from other collaborators and could make a major improvement to the experiment.

4.4 The Beam Dump

As noted above, the final resting place of the proton beam and any undecayed pions is the beam dump at the end of the decay region. The design of this component is difficult, as it experiences pulsed, high energy deposits, a high integrated lifetime radiation dose, must operate for the lifetime of the facility including during 4 MW operation, and is in a position where maintenance is essentially impossible. Simulations done at RAL show that there is still a problem with high local energy deposit and heating at the front face of the Cu block (and example of the RAL simulations is shown in Fig 12, which demonstrates that a Cu-core beam dump would break), and this is without taking fully into account shock effects. More engineering and design is essential, using specialist tools such as the LS-Dyna dynamical simulation computer code. It is very difficult for the Japanese to carry out such studies, as they have very limited technical manpower available to them and must rely on outside firms, which are expensive and difficult to interact closely with. RAL EID has proposed to take over and provide a complete engineering design of the beam dump. During the seedcorn period they would undertake studies of the current designs, figure out what testing and prototyping will be necessary to produce a full design, and then produce a fully costed proposal for producing the full engineering design for the dump core.

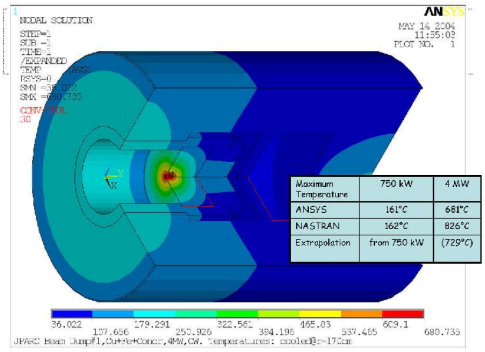


Figure 12 Example Beam Dump Simulation at RAL

4.5 The Target, Baffle, and Target Station

Almost certainly the most technically demanding aspect of the entire project is the target. Here the lack of engineering effort at KEK is perhaps even more serious, and even conceptual solutions have not yet been identified for all problems. This is a problem that goes far beyond T2K, as building a high-powered target is a necessary part of almost all future experiments with a proton driver, especially a Neutrino Factory. Experience gained working on the T2K target would therefore be of general use to the UK programme.

There are three separate but related elements in our proposed contributions to the target/target station. The first would be to integrate RAL EID engineering expertise into the T2K target design. We would conduct feasibility studies of the JPARC target concept for 0.75 MW operation, including thermal, mechanical, fluid flow, heat transfer, and especially shock response of the system. One important element of this would be to join a proposed experiment at CERN on the ISOLDE beam to test the shock wave performance of graphite rods and compare these to the predictions of simulations. A second major part of our involvement would be to look very critically at the design of the target baffle. This is intended to sit just upstream of the target and protect the horn from direct exposure to the beam, but the design of the component is extremely challenging. RAL proposes to take over the complete design of this component, with the intent of bidding to supply it in the full proposal. We would also provide expertise on the remote handling necessary for this component. Our third contribution would be to extend our study of remote handling needs to the target station as a whole, and, in particular, to the supply of remote handling clamps of a tested RAL design. This is an area where RAL expertise is considerable through years of experience on ISIS, and where the Japanese seem critically short of design engineering of tested (rather than conceptual) solutions. To give one example of how this could be critical to the project, the current plan is that if a target breaks it would be removed along with its cooling apparatus and the entire first horn and the complete assembly discarded as high-level waste. It seems unreasonable to discard so much expensive equipment because of the failure of a single carbon rod, but without RAL expertise in remote handling (so that the target rod could be replaced remotely) it is thought that there is little alternative. Some of the difficulty involved can be appreciated by looking at Fig 13, which shows how deeply the target is buried in the apparatus, much of which is delicate and all of which highly radioactive. Details of the proposed RAL work are presented in Annex 2.

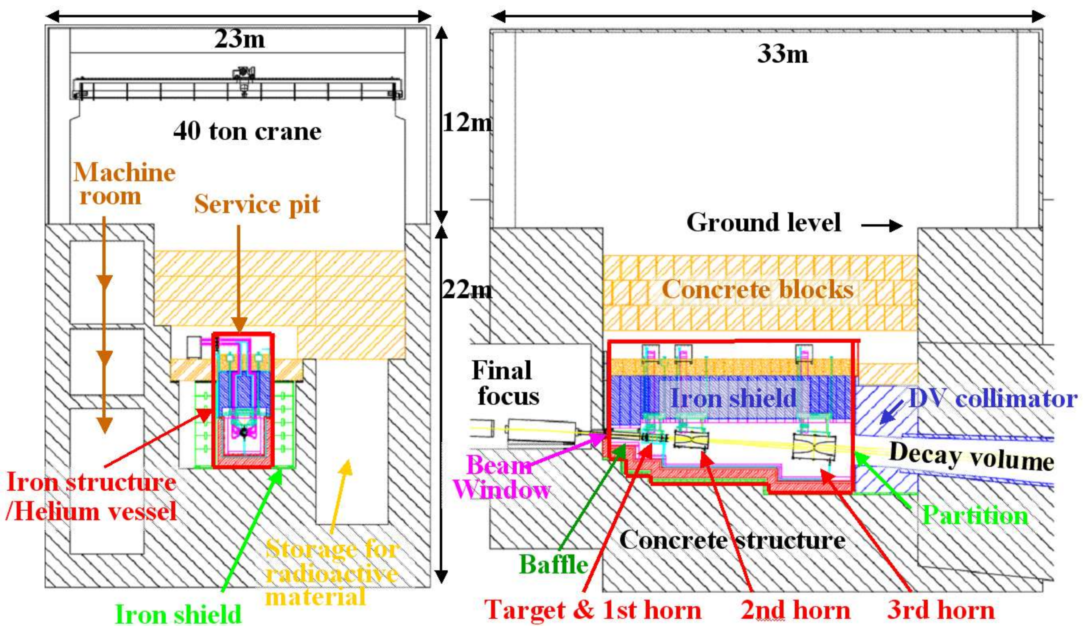


Figure 13 Layout of the target station.

which we estimate at £70k. The Sheffield group will need to set up a muon telescope to test water-based scintillators, which will require various equipment:

Mechanics, muon telescope, test cell :	2500
Scope to do waveform analysis: (Tek Wavepro) :	7500
Water purifier (15l/day), model EasyPure II UV :	1770
Water meter :	850
Consumables (storage, handling, etc.) :	800

Total: : £13420

Costs for the EID work are detailed in Annex 2. The total is 2.55 FTE staff years, calculated at £72/yr, makes £183.6k. £20k is sought for hardware for the ISOLDE tests, and an additional £4.5k is needed for licensing of the LS-Dyna software package. This makes the total sought from PPARC from seedcorn funds £291.52k.

Total through construction:

Here it becomes very difficult to estimate costs accurately, as we still have only incomplete ideas of the exact nature of the proposed UK participation in the project. Taking 4 years (Oct 05 – Oct 09) as the construction period we would assume that we would need ~£200k/annum for travel and support for people on site in Japan. We will, of course, need a large number of postdocs to deliver the project and to prepare the UK to get maximum return out of the data. We assume a profile of something like 7-10-10-10 for the postdocs (some of whom would be RG posts already in institutional grants), which makes 37 FTE of postdoc effort or something like £1554k. We have a commitment to seek funds to supply the magnet, which would add perhaps £150k. Remaining are the two largest items, which are difficult to cost until we have a much better idea what exactly we will provide. For the target/beam dump/target station we assume 4.5 FTE/yr for 3 years (only 3 years in order to get the design done on time), or 13.5 staff years @ £72k = £972k, to which one must add the actual hardware (plus manpower to fabricate it), which we estimate at £500k. The cost of the ECAL was guessed above at £2-4M. There is also RAL PPD effort not included in the above, that should cost ~350k over the 4 years. So the total is £6.35-8.35M, where the uncertainty is dominated by the cost of the ECAL which must be better specified next year.

Bibliography.

We have tried to supply more recent papers, which will contain references to earlier work by the same collaboration.

1. SAGE collaboration, recent results in astro-ph/0204245.
2. The Gallex collaboration, Phys.Lett.B447:127-133,1999.
3. Q.R. Ahmad *et al*., Phys. Rev. Lett. **89** (2001) 011301 and 011302.
4. For the latest KamLAND results see hep-ex/0406035.
5. Y. Fukuda *et al*., Phys. Rev. Lett. **81** (1998) 1562.
6. See M. Goodman, talk at Neutrinos '02, hep-ex/0210055.
7. See M. Goodman, talk at Neutrinos '02, hep-ex/0210055.
8. K2K collab., hep-ex/0406055.
9. A. Aguilar *et al*., Phys. Rev. D **64** (2002) 112007.
10. G.J. Drexlin, Prog. Part. Nucl. Phys. **48** (2002) 73.
11. The MiniBooNE collaboration, hep-ex/0408074
12. S.F. King, Rept.Prog.Phys.67:107-158,2004.
13. Many papers, for instanceW. Hu, D.J. Eisenstein, M. Tegmark, Phys. Rev. Lett. **80** (1998) 5255.
14. Many papers, for example astro-ph/0212/0212195.pdf
15. T. Yanagida, Nucl.Phys.Proc.Suppl.118:323-326,2003
16. For a review see the PDG, http://pdg.lbl.gov/2004/reviews/numixrpp.pdf
17. M. Apollonio *et al*., Phys. Lett. **B466** (1999) 415, A. Piepke *et al*., Prog. Part. Nucl. Phys. **48** (2002) 113.
18. R. Helmer, see http://www-jhf.kek.jp/NP02/Sep28/helmer.pdf
19. A huge literature, for instance see Huber *et al*., hep-ph/0211300.pdf
20. Minerva homepage: http://www.pas.rochester.edu/~ksmcf/minerva/

Further Information.

It is impossible to describe a $200M project in 20 pages. Additional information on T2K can be found at:

The T2K Homepage: http://neutrino.kek.jp/jhfnu/

A somewhat dated but very complete technical report:
http://jnusrv01.kek.jp/jnu/nu-TAC/jnuall-e.031029.pdf

Slides from the last collaboration meeting:
http://jnusrv01.kek.jp/jhfnu/NP04nu/program.html

Annex 2. Details of EID Work During Seedcorn Period (Oct. 04 – Oct. 05).

This proposal is to establish a program of work for RAL / Engineering and Instrumentation Department to carry out on the T2K target, beam dump and baffle. This will be done by formalizing an existing ad-hoc collaboration with JPARC staff who have requested our involvement with these items. Clear lines of responsibility and interfaces will be agreed in the course of the current year. Feasibility studies will be carried out leading to fully costed proposals by Spring 05.
All staff units are in %SY.

1 Beam Dump Core

Key RAL Responsibilities

It is proposed that RAL take key responsibility for the JPARC T2K beam dump core defined by those components within a radial envelope of 2.2 m and a z-direction envelope between 0 m and 8 m.
From Oct 04 to Oct 05 this responsibility is expected to cover:
1.1 Feasibility study of existing T2K beam dump outline concept for 4 MW operation. Highlight problems; make recommendations and investigate proposed improvements;
1.2 Design study including thermal and mechanical analysis of all beam dump components including heat transfer by water and air/He, using heat deposition data provided by JPARC staff;
1.3 Specification of prototyping and testing deemed necessary;
1.4 Specification of infrastructure requirements at JPARC i.e. services, instrumentation and civil engineering requirements for emergency remote handling.
1.5 Fully costed proposal for full engineering design of beam dump core;

1.1 Staff Resources

Chris Densham	20%	EID/ Engineering Analysis Group Leader
Mike Woodward	10%	EID/ Mechanical Design Group Leader
Peter Loveridge	20%	EID Project/analysis engineer
Simon Canfer / Derek Morrow	20%	EID Materials technologists
Designer	20%	EID staff
John Hirst	5%	ISIS Mechanical engineer / remote handling and graphite bonding expert
Hardware	£10k	

2 Target
Key RAL Responsibilities

2.1 Feasibility study of existing JPARC target concept for 750 kW operation. Develop outline design, highlight problems; make recommendations for new target designs and investigate alternatives;
2.2 Perform thermal, mechanical, fluid flow and heat transfer analysis of target, cooling system and mechanical support system, using ANSYS and CFX codes.
2.3 Develop remote handling concepts and designs for target and cooling system.

2.4 Specification of infrastructure and services requirements at JPARC i.e. cooling, instrumentation and remote handling. Develop target station layout concepts in collaboration with JPARC staff.
2.5 Join collaboration to specify and perform shock wave studies of graphite material using intense pulsed proton beam at ISOLDE facility at CERN. Use LS-Dyna code to analyse results and assess implications for T2K target.
2.6 Specification of tests for target manufacture and cooling methods.
2.2 Staff Resources

Chris Densham	30%	EID/ Engineering Analysis Group Leader
Mike Woodward	10%	EID/ Mechanical Design Group Leader
Peter Loveridge	20%	EID Project/analysis engineer
John Butterworth	20%	EID Analysis engineer
Simon Canfer / Derek Morrow	10%	EID Materials technologists
Designer	20%	EID staff
John Hirst	5%	ISIS Mechanical engineer / remote handling and graphite bonding expert
Hardware	£10k	
LS-Dyna license share	£4.5k	

3 Baffle

Key RAL Responsibilities

Complete responsibility for design, thermal and mechanical analysis and manufacture of the baffle, mechanical support and monitoring and of any cooling system if required.
Includes an assessment of consequences of different beam steering failures to determine the risk of baffle failure and consequent need for remote handling for replacement.
Space envelope and performance specification of baffle to be determined by JPARC.

3.1 Staff Resources

Chris Densham	10 %	EID/ Engineering Analysis Group Leader
Mike Woodward	5 %	EID/ Mechanical Design Group Leader
Peter Loveridge	10 %	EID Project/analysis engineer
Designer	10 %	EID staff

4 Remote handling systems

Key RAL Responsibilities

Investigation of requirements for remote handling and clamps etc. for entire T2K project.
Prepare a costed list and specification of what RAL can supply.

Chris Densham	5%	EID/ Engineering Analysis Group Leader
Mike Woodward	5%	EID/ Mechanical Design Group Leader
John Hirst	10%	ISIS Mechanical engineer / remote handling expert

5 Summary of RAL EID resources requested

Chris Densham	65%	EID/ Engineering Analysis Group Leader
Mike Woodward	30%	EID/ Mechanical Design Group Leader
Peter Loveridge	50%	EID Project/analysis engineer
John Butterworth	20%	EID Analysis engineer
Simon Canfer / Derek Morrow	30%	EID Materials technologists
Designer	40%	EID staff
John Hirst	20%	ISIS Mechanical engineer / remote handling and graphite bonding expert

Hardware		£20k
LS-Dyna	license share	£4.5k

Annex 3. Schedule for the Construction of JPARC/T2K

Japanese fiscals years are April-April.