Plans for super-beams in Japan

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Abstract
In Japan, as the first experiment utilizes J-PARC (Japan Proton Accelerator Research Complex) neutrino facility, T2K (Tokai to Kamioka Long Baseline Neutrino Experiment) starts operation. T2K is supposed to give critical information, which guides the future direction of the neutrino physics. Possible new generation discovery experiment based on T2K outcome is discussed. Especially, description of J-PARC neutrino beam upgrade plan and discussion on far detector options to maximize potential of the research are focused. European participation and CERN commitment on Japanese accelerator based neutrino experiment is also reported.

1 J-PARC and Main Ring Synchrotron

J-PARC (Figure 1) is a KEK-JAEA joint facility for MW-class high intensity proton accelerator. It provides unprecedented high flux of various secondary particles, such as neutrons, muons, pions, kaons, and neutrinos, which are utilized for elementary particle physics and material and life science.

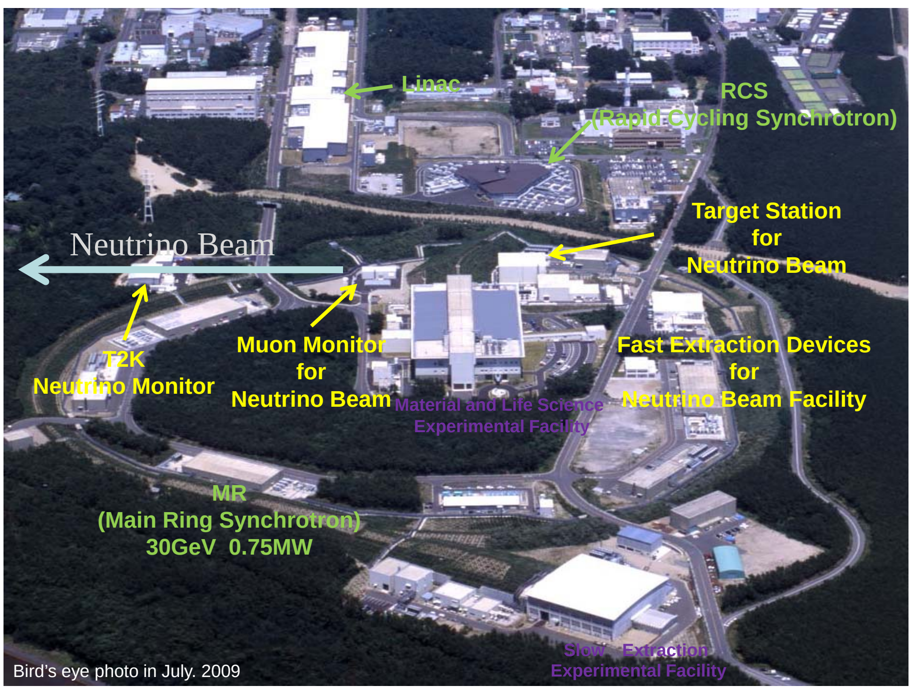
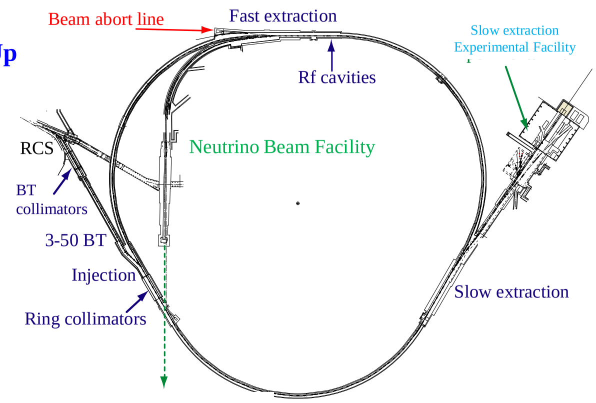


Fig. 1: J-PARC accelerator and experimental facility

In the accelerator complex, H^- ions are accelerated to 181 MeV with LINAC, fed into Rapid Cycling Synchrotron (RCS) with stripping out electrons and are accelerated to 3 GeV. At final stage, proton beam goes into Main Ring Synchrotron (MR) and accelerated to 30 GeV. For the neutrino experiment, accelerated protons are kicked inward to neutrino beam facility by single turn with fast extraction devices. Main characteristics of MR is described in Figure 2.

Circumference	**1567.5 m**
Repetition rate	**∼0.3 Hz@Start Up**
Injection energy	**3 GeV**
Extraction energy	**30 GeV**
Superperiodicity	**3**
h	**9**
No. of bunches	**8 (6@Start Up)**
Transition γ	**31.7(imaginary)**
Typical tune	**22.4, 20.8**
Transverse emittance	
At injection	**~54 πmm-mrad**
At extraction	**~10 πmm-mrad**
Beam power	**0.75MW**



Three dispersion free straight sections of 116-m long:
- Injection and collimator systems
- Fast extraction (beam is extracted inside/outside of the ring) and RF cavities
  inside: Neutrino Beam Facility (intense ν beam to the west)
  outside: Beam abort line
- Slow extraction
  to Slow extraction Experimental Facility
  (K Rare decay, Muon Lepton Flavor Violation, etc.)

Fig. 2: Overview of MR

2 J-PARC neutrino beam facility

The proton beam from MR run through J-PARC neutrino beam facility and producing intense muon neutrinos toward the west direction. J-PARC neutrino beam facility is composed of following parts with their functionalities (Figure 3).

- Preparation section: Match the beam optics to the arc section.
- Arc section: Bend the beam $\sim$90° toward the west direction with superconducting combined function magnet.
- Final focus section: Match the beam optics to target both in position and in profile. Level of mm control is necessary which corresponds to 1 mrad ν direction difference, also not to destroy target.
- Graphite target and horn magnet: Produce intense secondary π's and focus them to the west direction. (3 horns system with 320 kA pulse operation)
- Muon monitor: Monitor μ direction ($= \nu$ direction), pulse to pulse, with measuring center of muon profile.
- On-axis neutrino monitor (INGRID): Monitor ν direction and intensity.

This facility is designed to be tolerable up to $\sim$2 MW beam power. The limitation is due to temperature rise and thermal shock for the components such as Al horn, graphite target, and Ti vacuum window. Since everywhere suffers from high radiation, careful treatment of radioactive water and air ($\sim$10 GBq/3weeks) is required. Moreover, maintenance scenario of radio active components has to be seriously planned.

On 23rd April 2009, commissioning of the facility started with the real proton beam which was delivered by MR. The very first shot of the proton beam, after all the beam line magnet turned on, steered into target station and muon monitor clearly indicated production of intense muons which certified associated neutrino production. After 9 shots of tuning, the beam is centered on the target. With subsequent tuning and measurement, followings are achieved.

- Stability of the extraction beam orbit from MR is confirmed. It is tuned within 0.3 mm in position and 0.04 mrad in direction w.r.t. design orbit.

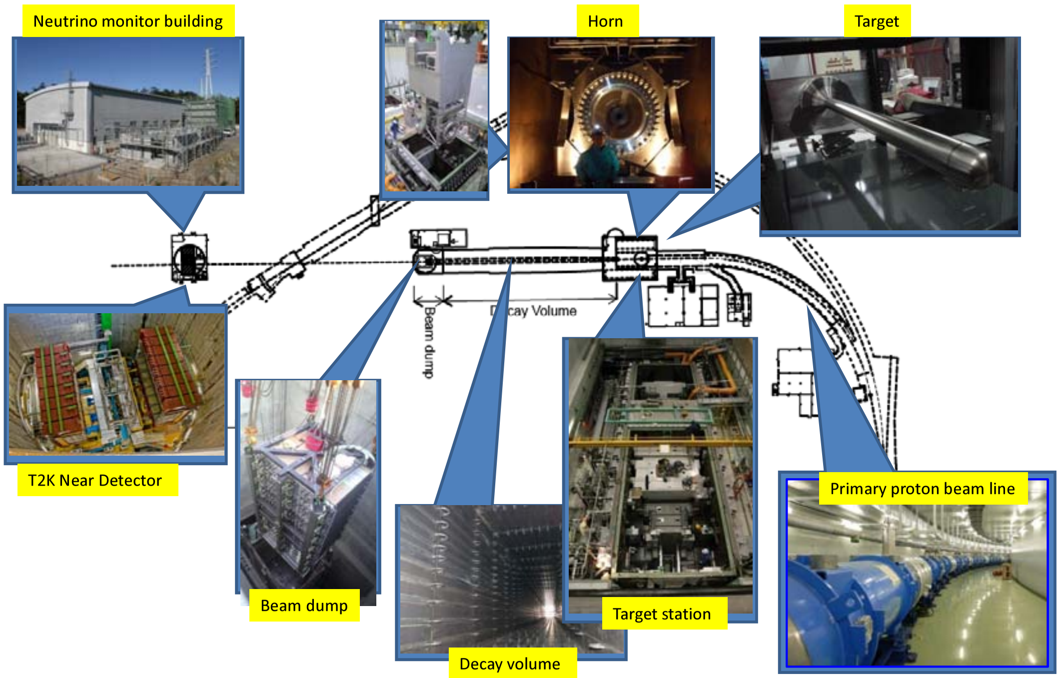


Fig. 3: J-PARC neutrino beam facility

- Functionality of the superconducting combined function magnet is confirmed.
- Beam is lead to the target center without significant beam loss. Beam trajectory is tuned within 3 mm level accuracy w.r.t. design orbit.
- Functionality of the beam monitors (beam position, beam profile, beam intensity and beam loss) are confirmed.
- Response function of various magnets are measured.
- Muon signal is observed which confirms neutrino production. (Muon direction corresponds to neutrino direction and muon yield corresponds to neutrino yield.)
- The effect of pion focusing with horn magnet is confirmed. ($\times 2$ which is consistent with horn configuration at that time.)
- The information transfer from Tokai to Kamioka on the absolute beam time information is confirmed.
- J-PARC neutrino facility is approved by the government on radiation safety.

The next running of the facility is foreseen from October 2009 with following MR intensity improvement. Production data taking for neutrino experiment is foreseen to start in January 2010.

3 T2K

T2K [1] is the first experiment with J-PARC neutrino beam. With the combination of unprecedented high intensity neutrino source and a well established neutrino detector, Super-Kamiokande (SK), as a far main detector, T2K will seeks for ν_μ to ν_e conversion phenomenon and, as a consequence, measures an finite value of one of the neutrino mixing angle, θ_{13}, with an order of magnitude better sensitivity compared to the prior experiments at an atmospheric neutrino anomaly regime. T2K also conduct precision measurement of another neutrino mixing angle, θ_{23}. Moreover, something unexpected in neutrino physics may be revealed by T2K.

The baseline of 295 km and off-axis angle of 2.5° are optimized, 1) to maximize neutrino flux at the neutrino energy of the first oscillation maximum, 2) to avoid severe π^0 background originated from high energy neutrino interaction, and 3) to tune neutrino energy range to be optimum for a water cherenkov detector (sub GeV energy region, low multiplicity and quasi elastic interaction dominant).

The properties of the produced neutrino beam are measured by a system of near detectors at J-PARC which consists of two major parts, one is on-axis neutrino monitor (INGRID) which monitors neutrino direction, intensity and its stability, and the other is an assembly of detectors located 2.5° off-axis direction as SK (ND280), which measures not only neutrino flux as is expected at SK but also sub GeV neutrino interaction which gives important information for neutrino oscillation analysis in T2K. The most outer part of the ND280 is the UA1/NOMAD magnet, which provides the magnetic field used to determine the momentum of charged particles originated from neutrino interaction. Inside the magnet, Fine Grain Detector (FGD) which is an active neutrino target, Time Projection Chamber (TPC) which measures any charged particles emerged from neutrino interaction, π^0 detector (POD) which is optimized for measuring the rate of neutral current π^0 production, Electromagnetic Calorimeter (ECAL) which reconstructs any electromagnetic energy produced, and Side Muon Range Detector (SMRD) which is instrumented in the magnet yokes to identify muons from neutrino interaction, are located. The status of detectors as of October 2009 is shown in Figure 4.

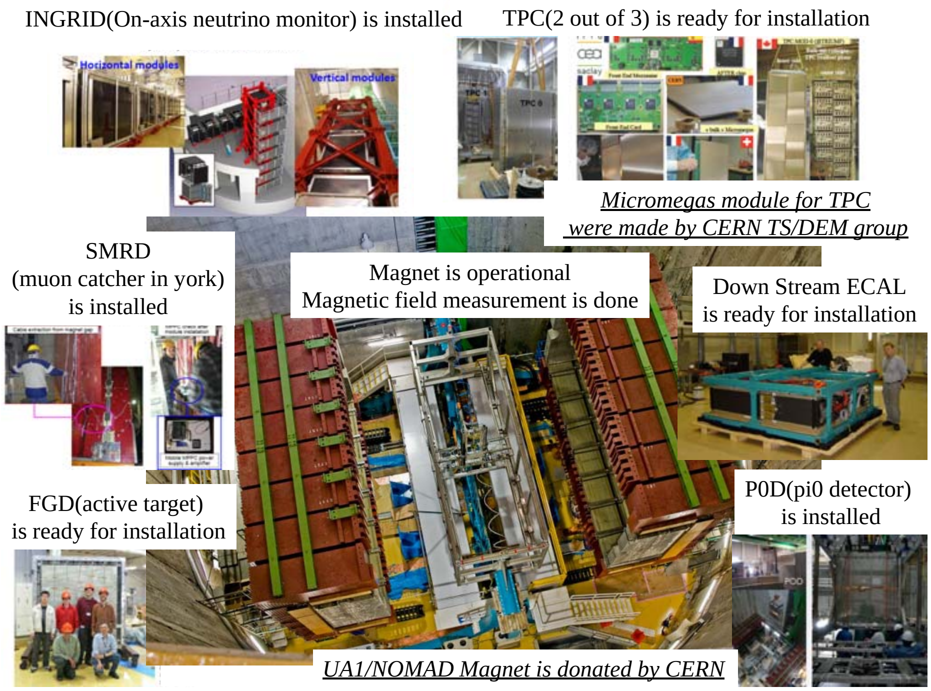


Fig. 4: Status of the T2K near site neutrino detectors as of October 2009

As a first milestone, T2K is aiming for the first results in 2010 with 100 kw $\times$ 10^7 seconds integrated proton power on target to unveil below the CHOOZ experimental limit [2] with ν_e appearance.

4 European and CERN commitment on Japanese accelerator based neutrino experiment

European participation in Japanese accelerator based neutrino experiment began at K2K (KEK to Kamioka Long Baseline Neutrino Experiment). France, Italy, Poland, Russia, Spain and Switzerland joined this world first accelerator based long baseline neutrino experiment. When T2K project started, Germany and United Kingdom also participated. As of October 2009, T2K collaboration consists of 477 members from 62 institutes spread out 12 coutries. Composition is, 240 (50.3%) members from Europe, 84 (17.6%) members from Japan, 77 (16.1%) members from USA, 68 (14.3%) members from Canada and

8 (1.7%) members from South Korea, as shown in Figure 5.

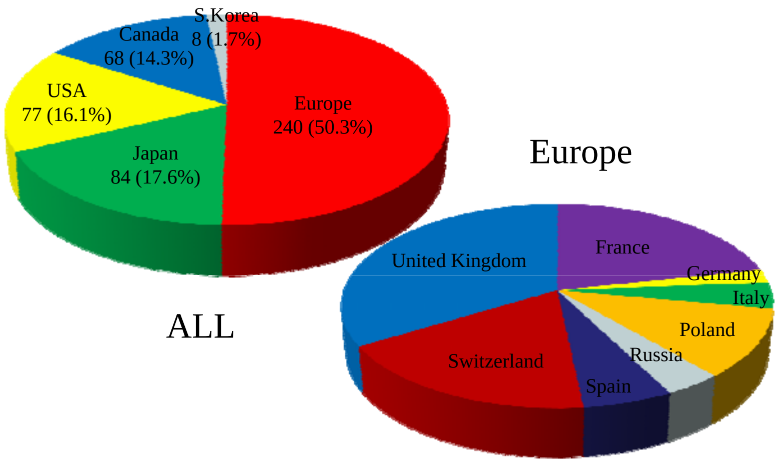


Fig. 5: Participants for T2K

T2K is registered as Recognized Experiment at CERN (RE13) and CERN extensively supports T2K. Followings are the list of CERN support for T2K.

- CERN experiment NA61: This experiment is indispensable part of T2K to understand neutrino flux for the experiment.
- CERN test beam for detectors.
- Donation of UA1/NOMAD magnet.
- Micromegas production and its test conducted by CERN TS/DEM group.
- Various technical, administrative support on detector preparation, especially for UA1/NOMAD magnet related issues.
- Infrastructure for detector preparation.
- CERN-KEK cooperation on super conducting magnet for neutrino beam line.

KEK feels grateful to CERN for all the aspect of support provided by CERN.

5 New generation accelerator based neutrino experiment in Japan

The primary motivation of T2K is to improve the sensitivity to the $\nu_\mu \to \nu_e$ conversion phenomenon in the atmospheric regime. The final goal for T2K is to accumulate an integrated proton power on target of 0.75 MW$\times 5 \times 10^7$ seconds. As is shown in Figure 6, within a few years of run, critical information, which will guide the future direction of the neutrino physics, will be obtained based on the data corresponding to about 1 to 2 MW$\times 10^7$ seconds integrated proton power on target (roughly corresponding to a 3σ discovery at $\sin^2 2\theta_{13} > 0.05$ and 0.03, respectively).

If a significant $\nu_\mu \to \nu_e$ coversion signal were to be observed at T2K, an immediate step forward to a next generation experiment aimed at the discovery of CP violation in the lepton sector would be recommended with high priority. Compared with T2K experimental conditions, lepton sector CP violation discovery requires

- an improved J-PARC neutrino beam intensity;
- an improved main far neutrino detector.

Detector improvements include

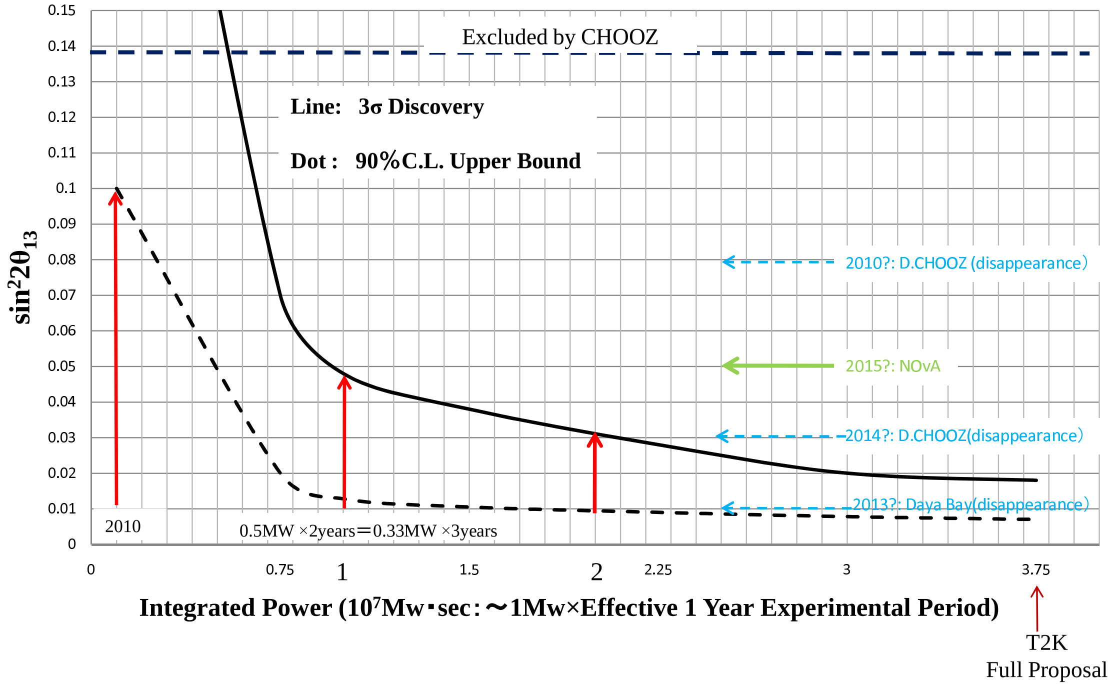


Fig. 6: T2K dicovery potential on $\nu_\mu \to \nu_e$ as a function of integrated proton power on target

- detector technology;
- its volume;
- its baseline and off-axis angle with respect to the neutrino source.

Naturally, next generation far neutrino detectors for lepton sector CP violation discovery will be very massive and huge. As a consequence, the same detector will give us the rare and important opportunity to discover proton decay. A total research subject would be, to address a long standing puzzle of our physical world, the "Quest for the Origin of Matter Dominated Universe" (see e.g. [3]), with exploration of

- the Lepton Sector CP Violation by precise testing of the neutrino oscillation processes;
  - measure precisely the CP phase in lepton sector (δ) and the mixing angle θ_{13};
  - examine matter effect in neutrino oscillation process and possibly conclude the mass hierarchy of neutrinos.
- Proton Decay:
  - Search for p $\to \nu$ K$^+$ and p $\to$ e π^0 in the life time range 10^{34} to 10^{35} years,

with assuming non-equilibrium environment in the evolution of universe.

Even in case that $\sin^2 2\theta_{13}$ is below T2K sensitivity, it is still worth while trying to improve J-PARC neutrino beam intensity and far detector performance to open the way to explore $\nu_\mu \to \nu_e$ conversion phenomenon with by an order of magnitude better sensitivity [5].

This direction of research is endorsed by KEK Roadmap defined in 2008, in which J-PARC neutrino intensity improvement and R&D to realize huge detector for neutrino and proton decay experiments are the two of the main subject. KEK has started R&D to realize huge liquid Argon time projection chamber.

5.1 J-PARC neutrino beam upgrade plan

As for the neutrino beam intensity improvement, MR power improvement scenario toward MW-class power frontier machine, KEK Roadmap plan, is analyzed and proposed by the J-PARC accelerator team as shown in Table 1.

Table 1: MR power improvement scenario toward MW-class power frontier machine (KEK Roadmap)

	Start Up	Next Step	**KEK Roadmap**	Ultimate
Power (MW)	0.1	0.45	**1.66**	?
Energy (GeV)	30	30	**30**	
Rep. Cycle (sec.)	3.5	3-2	**1.92**	
No. of Bunches	6	8	**8**	
Particles/Bunch	1.2×10^{13}	$<4.1\times10^{13}$	$\mathbf{8.3\times10^{13}}$	
Particles/Ring	7.2×10^{13}	$<3.3\times10^{14}$	$\mathbf{6.7\times10^{14}}$	
LINAC (MeV)	181	181	**400**	
RCS[a]	h=2	h=2 or 1	**h=1**	

[a] Harmonic number of RCS

Items to be modified from start up toward high intensity are listed as following.

- Number of bunches in MR should be increased from 6 to 8. For this purpose, fast rise time extraction kicker magnet have to be prepared. Its installation is foreseen in 2010 summer.
- Repetition cycle of MR has to be improved from 3.5 seconds to 1.92 seconds. For this purpose RF and magnet power supply improvement is necessary.
- RCS operation wih harmonic number 1 has to be conducted. This is to make the beam bunch to be longer in time domain to decrease space charge effect. For this purpose RF improvement is necessary. When RCS is operated with harmonic number 2, beam is injected to MR with 2 bunches $\times$ 4 cycles. On the other hand, when RCS is operated with harmonic number 1, beam is injected to MR with single bunch with doubled number of protons $\times$ 8 cycles.
- LINAC 400 MeV operation is required to avoid severe space charge effect at RCS injection. Construction of necessary component is already approved and started.

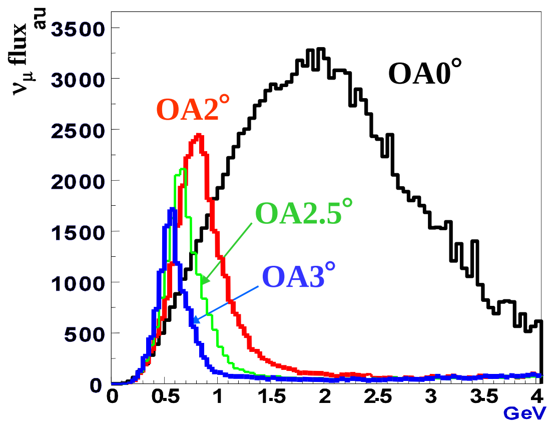
5.2 Far detector options: How to approach Lepton Sector CP Violation

The effects of CP phase δ appear either

- as a difference between ν and $\bar{\nu}$ behaviors (this method is sensitive to the CP-odd term which vanishes for $\delta = 0$ or 180°);
- in the energy spectrum shape of the appearance oscillated ν_e charged current events (sensitive to all the non-vanishing δ values including 180°).

It should be noted that if one precisely measures the ν_e appearance energy spectrum shape (peak position and height for 1st and 2nd oscillation maximum and minimum) with high resolution, CP effect could be investigated with neutrino run only. Antineutrino beam conditions are known to be more difficult than those for neutrinos (lower beam flux due to leading charge effect in proton collisions on target, small antineutrinos cross-section at low energy, etc.).

Figure 7 (left) shows neutrino flux for vaious off-axis angles. If one selects on-axis setting, 1) wide energy coverage is foreseen which is necessary to cover the 1st and 2nd maximum simultaneously, and 2) measurement suffers from severe π^0 background originated from high energy neutrino which requires



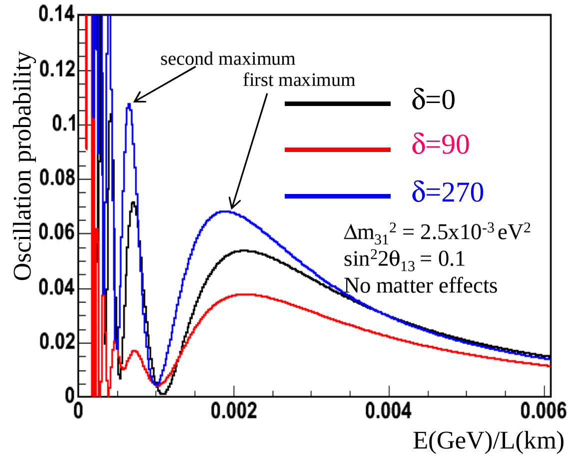


Fig. 7: Neutrino flux for various off-axis angle (left) and Probability for $\nu_\mu \to \nu_e$ oscillations as a function of the E(GeV)/L(km) for various δ. (right)

the detector with high performance discrimination ability between π^0 and electron. On the other hand, if one selects off-axis setting, 1) requirement for π^0 background discrimination is soft, and 2) measurement is essentially counting experiment at the 1st oscillation maximum.

Figure 7 (right) shows the oscillation probability as a function of the E(GeV)/ L(km). If the distance between source and detector is fixed, the curves can be easily translated to that for the expected neutrino energy spectrum of the oscillated events. As can be seen, if the neutrino energy spectrum of the oscillated events could be reconstructed with sufficiently good resolution in order to distinguish first and second maximum, useful information to extract the CP phase would be available even only with a neutrino run. If baseline is set to be long, 1) energy of 2nd oscillation maximum gets measurable. 2) statistical significance may get worse, and 3) measurement is affected by large matter effect. On the other hand, if baseline is set to be short, 1) it is impossible to extract 2nd oscillation maximum information, 2) statistical significance may get better, and 3) measurement is less affected by matter effect.

To define far detector option, discovery potential for proton decay and reality to realize huge one are also the essential issues to be taken into account.

5.3 Possible scenarios for new generation discovery experiment with J-PARC neutrino beam

The study of possible new generation discovery experiments with J-PARC neutrino beam was initiated at the 4th International Workshop on Nuclear and Particle Physics at J-PARC (NP08) [4]. With the same configuration as T2K (2.5° off-axis angle), the center of the neutrino beam will go through underground beneath SK (295 km baseline), and will automatically reach the Okinoshima island region (658 km baseline) with an off-axis angle 0.8° (almost on-axis) and eventually the sea level east of the Korean shore (1,000 km baseline) with an off-axis angle $\sim 1°$.

5.3.1 Scenario 1: J-PARC to Okinoshima Long Baseline Neutrino Experiment

The first scenario is "J-PARC to Okinoshima Long Baseline Neutrino Experiment" as shown in Fig. 8 [5]. In order to cover a wider energy range, detector location which is near on-axis is favored. If one assumes that the second oscillation maximum has to be located at an energy larger than about 400 MeV, the baseline should be longer than about 600 km. In addition, in order to collect enough statistics, baseline should not be too much longer than above stated. Taking into account all of the above mentioned considerations, the Okinoshima region (658 km baseline and almost on-axis (0.8° off-axis) configuration) turns out to be ideal.

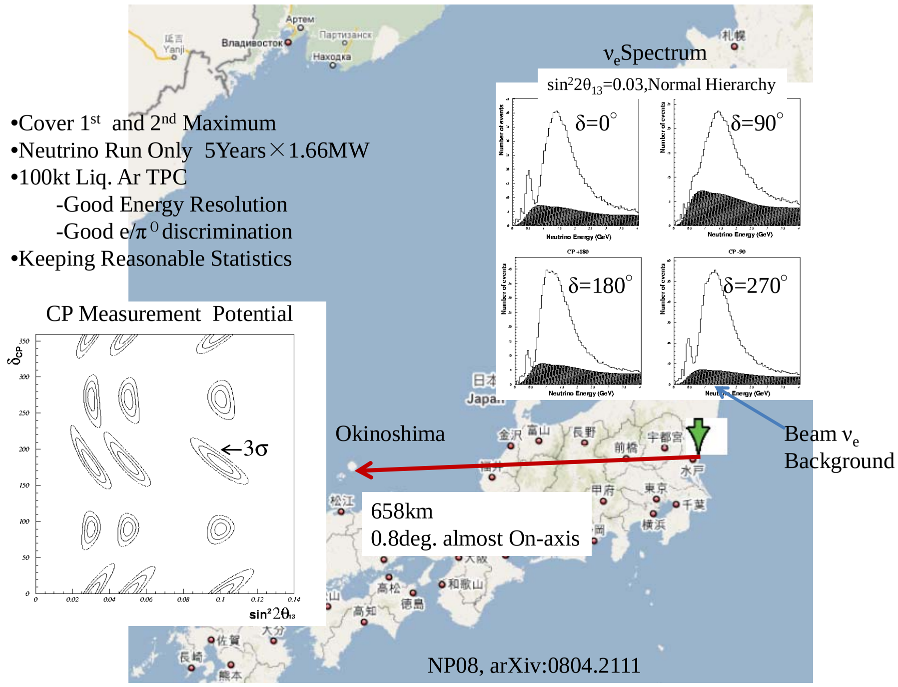


Fig. 8: Scenario 1: J-PARC to Okinoshima Long Baseline Neutrino Experiment

Analysis here based on the assumption using a neutrino run only during five years to be reasonable time duration for the single experiment (10^7 seconds running period/year is assumed), under the best J-PARC beam assumption. An anti-neutrino beam (opposite horn polarity) might be considered in a second stage in order to cross-check the results obtained with the neutrino run (in particular for mass hierarchy problem). Detector is assumed to be a 100 kton liquid Argon time projection chamber. This type of detector is supposed to provide higher precision than other huge detectors to separate the two peaks in energy spectrum. In addition, the π^0 background is expected to be highly suppressed thanks to the fine granularity of the readout, hence the main irreducible background will be the intrinsic ν_e component of the beam. The right hand side plot in Figure 8 shows the energy spectra of electron neutrino at the cases of δ equal 0°, 90°, 180°, 270°, respectively. Shaded region is common for all plots and it shows the background from beam ν_e. Here perfect resolution is assumed. As shown, the value of δ varies the energy spectrum, especially the first and the second oscillation peaks (heights and positions), therefore comparison of the peaks determine the value δ, while the value of $\sin^2 2\theta_{13}$ changes number of events predominantly. Allowed regions in the perfect resolution case are shown in left hand side of Figure 8. Twelve allowed regions are overlaid for twelve true values, $\sin^2 2\theta_{13}$=0.1, 0.05, 0.02, and δ=0°, 90°, 180°, 270°, respectively. The δ sensitivity is 20∼30° depending on the true δ value.

5.3.2 Scenario 2: J-PARC to Kamioka Long Baseline Neutrino Experiment

Second scenario is "J-PARC to Kamioka Long Baseline Neutrino Experiment" as shown in Fig. 9 [4]. The concept is same as T2K except for huge detector size whose fiducial volume is assumed to be 570 kt. The baseline of 295 km and off-axis angle of 2.5° are optimum for the experimental sensitivity with a water cherenkov detector as they are for T2K. With this configuration, on the other hand, it is only possible to cover 1st oscillation maximum. In order to investigate difference between neutrino and anti-neutrino behavior with sufficient statistics, 2.2 years (10^7 seconds running period/year is assumed) neutrino run and 7.8 years anti-neutrino run is required. Since the cancellation of systematic uncertainty between neutrino run and anti-neutrino run is not much expected, the way to deal with delicate systematic uncertainty is a important issue to be seriously considered.

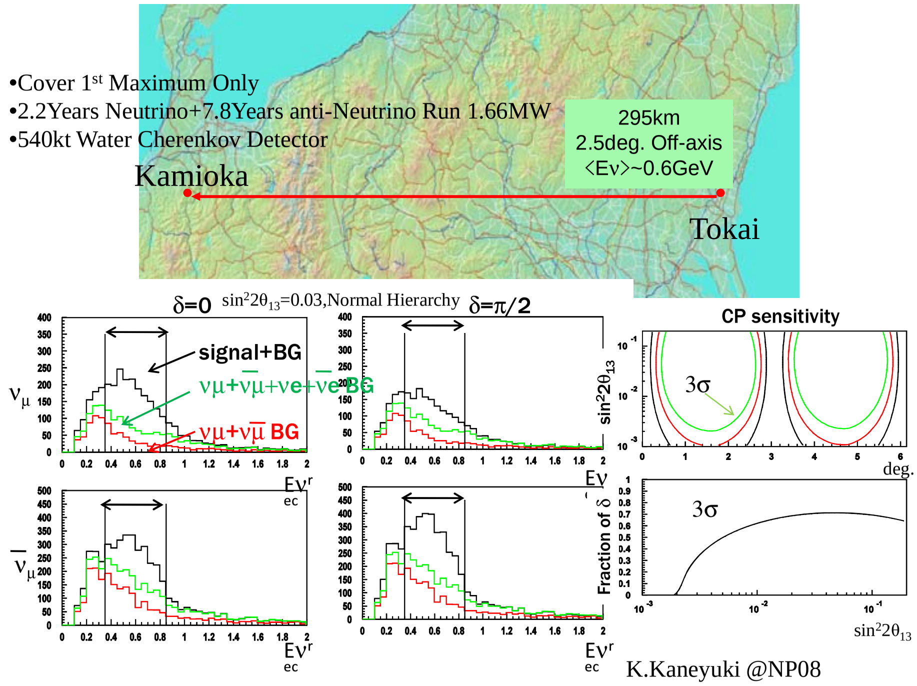


Fig. 9: Scenario 2: J-PARC to Kamioka Long Baseline Neutrino Experiment

5.3.3 *Scenario3: J-PARC to Kamioka and Korea Long Baseline Neutrino Experiment*

Third scenario is "J-PARC to Kamioka and Korea Long Baseline Neutrino Experiment" as shown in Fig. 10 [4]. This plan is partially same as scenario 2. In order to obtain 1st and 2nd oscillation maxima information, in addition to neutrino and anti-neutrino difference, two 270 kt water cherenkov detectors, one at Kamioka (295 km baseline) and the other in Korea (1,000 km baseline) are utilized. It would allow to study E/L regions corresponding to the 1st oscillation maximum at Kamioka and 2nd oscillation maximum at Korea, at the suitable energy regime for the measurement with a water cherenkov detector. It requires five years each for neutrino and anti-neutrino run.

Comparison of each scenario is shown in Table 2. Study is continuing to seek for optimum choice to maximize potential of the research.

Table 2: Comparison of possible scenarios for new generation discovery experiment with J-PARC neutrino beam

	Scenario 1 **Okinoshima**	**Scenario 2** **Kamioka**	**Scenario 3** **Kamioka and Korea**
Baseline (km)	658	295	295 and 1000
Off-Axis Angle (°)	0.8(almost on-axis)	2.5	2.5 and 1
Method	ν_e Spectrum Shape	Ratio between ν_e and $\bar{\nu}_e$	Ratio between 1st and 2nd Max. Ratio between ν_e and $\bar{\nu}_e$
Beam	5 years ν_μ then Decide Next	2.2 years ν_μ and 7.8 years $\bar{\nu}_\mu$	5 years ν_μ and 5 years $\bar{\nu}_\mu$
Detector Technology	Liq. Ar TPC	Water Cherenkov	Water Cherenkov
Detector Mass (kt)	100	2×270	270+270

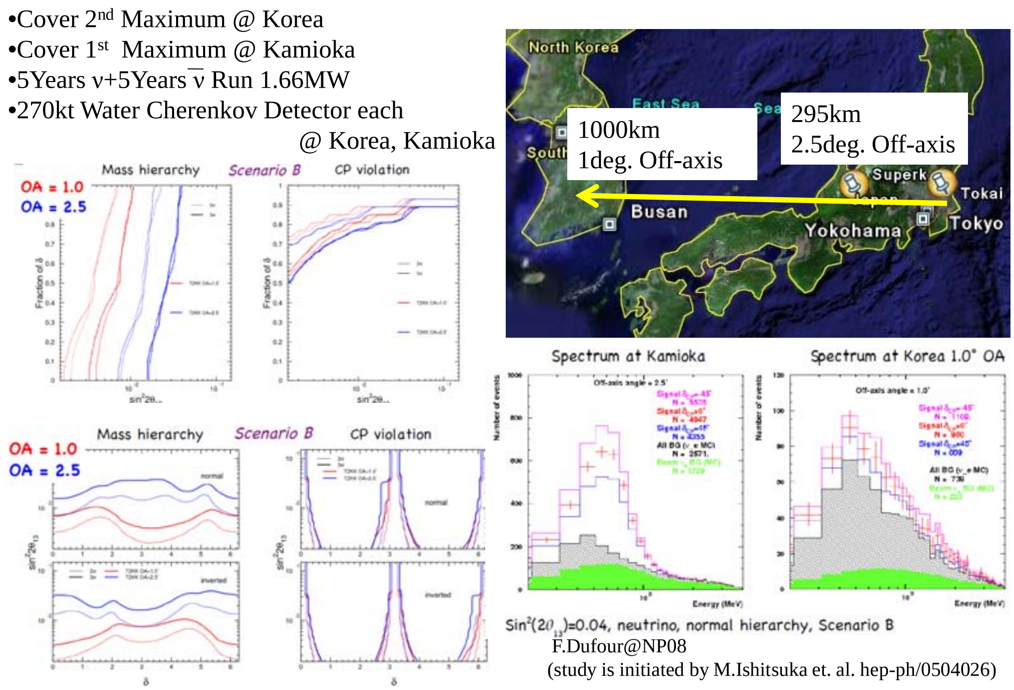


Fig. 10: Scenario 3: J-PARC to Kamioka and Korea Long Baseline Neutrino Experiment

6 Accelerator based neutrino project in Japan

Table 3 summarizes accelerator based neutrino project in Japan. When K2K and T2K projects started, the existence of high performance far main detector, SK, made it possible to concentrate on neutrino beam source related preparation. As for the 3rd generation experiment, the existence of J-PARC neutrino beam make it possible to concentrate on far detector issues after T2K starts up.

Table 3: Accelerator based neutrino project in Japan

	K2K	T2K	**3rd Generation Experiment**
High Power Proton Synchrotron	KEK PS 12GeV 0.005MW Existing	J-PARC MR 30GeV 0.75MW Brand New	**J-PARC MR** **30GeV 1.66MW** **Technically Feasible Upgrade**
Neutrino Beamline	K2K Neutrino Beamline Brand New	J-PARC Neutrino Beamline Brand New	**J-PARC** **Neutrino Beamline** **Existing**
Far Detector	Super Kamiokande Existing at KAMIOKA	Super Kamiokand Existing at KAMIOKA	**Brand New** **- Detector Technology ?** **- Place (Angle and Baseline) ?**
1st Priority Physics Case	Neutrino Oscillation ν_μ Disappearance	Neutrino Oscillation $\nu_\mu \to \nu_e$	**Lepton Sector CP Violation** **Proton Decay**

To complete present project T2K successfully and realize new generation discovery experiment, following issues are important.

- Deliver high quality experimental output from T2K as soon as possible.
- Realize quick improvement of accelerator power toward MW-class power frontier machine.
- Validate beam line components tolerance (especially pion production target related issues) toward MW proton beam.
- Conduct intensive R&D on realization of huge liquid Argon time projection chamber and water cherenkov detector.

Healthy scientific competition and cooperation in the world is key to promote high energy physics. It is welcomed to cooperate in any aspects.

In Japan we will proceed as following.

- Short term
  - Beam commissioning of J-PARC MR has started May-2008.
  - Commissioning of J-PARC neutrino beam facility has started in April-2009.
  - T2K is aiming for the first results in 2010 with 100 kw $\times$ 10^7 seconds integrated proton power on target to unveil below CHOOZ experimental limit with ν_e appearance.
- Middle term
  - T2K data with 1-2 MW $\times$ 10^7 seconds integrated proton power on target will provide critical information on θ_{13}, which guides the future direction of the neutrino physics. (In any case, complete T2K proposal of 3.75 MW $\times$ 10^7 seconds.)
  - Achieve MR power improvement scenario toward MW-class power frontier machine (KEK Roadmap).
  - Submit proposal "J-PARC to Somewhere Long Baseline Neutrino Experiment and Nucleon Decay Experiment with Huge Detector" and construct huge detector.
- Long term
  - Discover CP violation in lepton sector and proton decay, and solve “Quest for the Origin of Matter Dominated Universe"

References

[1] Y. Itow *et al.*, “The JHF-Kamioka neutrino project,” arXiv:hep-ex/0106019.

[2] M. Apollonio *et al.* [CHOOZ Collaboration], “Limits on neutrino oscillations from the CHOOZ experiment,” Phys. Lett. B **466**, 415 (1999)

[3] G. Steigman Ann.Rev.Astron.Astrophys, 14(1976)339; A.D. Sakharov Pisma Zh.ETF 5(1967)32.

[4] Talk given at the 4th International Workshop on Nuclear and Particle Physics at J-PARC (NP08). Slides available at `http://j-parc.jp/NP08/`

[5] A. Badertscher, T. Hasegawa, T. Kobayashi, A. Marchionni, A. Meregaglia, T. Maruyama, K. Nishikawa and A. Rubbia, “ A Possible Future Long Baseline Neutrino and Nucleon Decay Experiment with a 100 kton Liquid Argon TPC at Okinoshima using J-PARC Neutrino Facility,” arXiv:0804.2111