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.

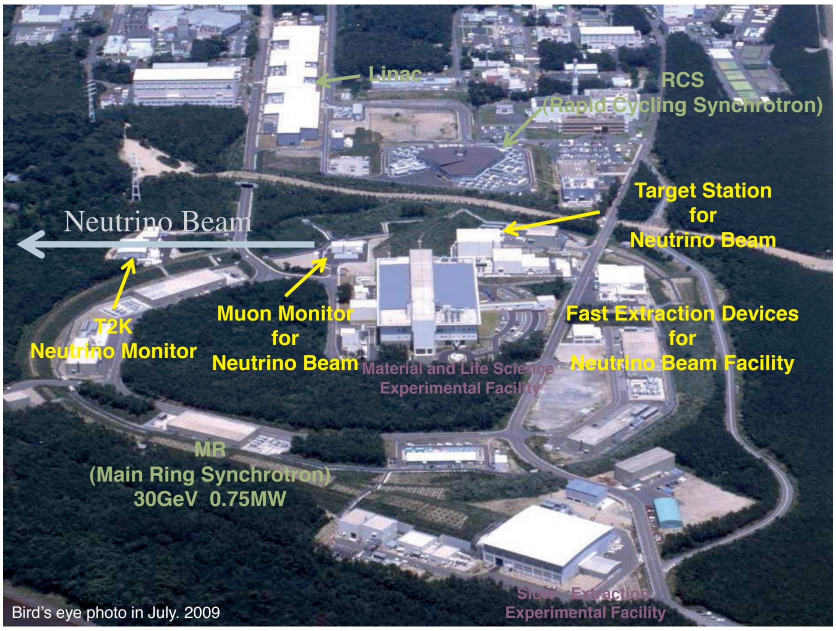
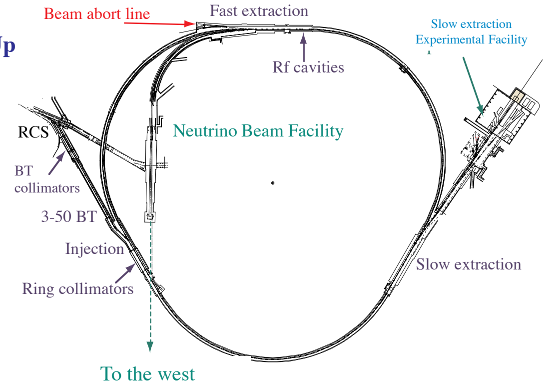


Fig. 1: J-PARC accelerator and experimental facility

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 $\sim 90^\circ$ 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.

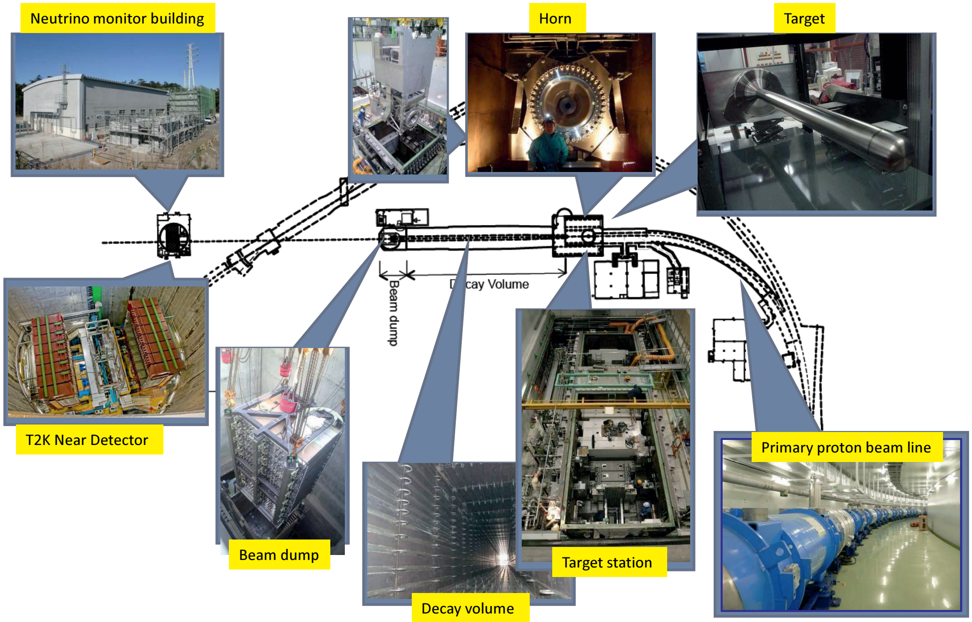


Fig. 3: J-PARC neutrino beam facility

- 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.

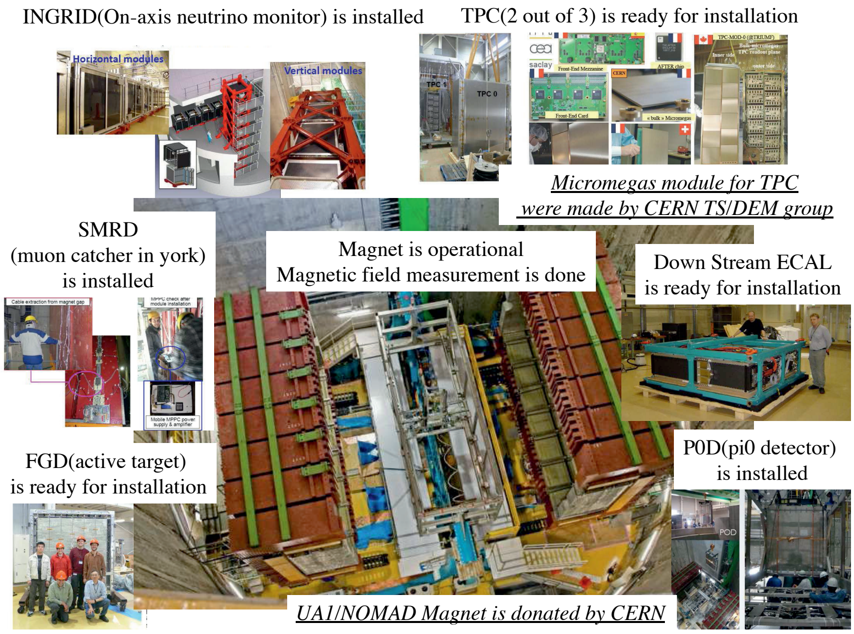


Fig. 4: Status of the T2K near site neutrino detectors as of October 2009

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.

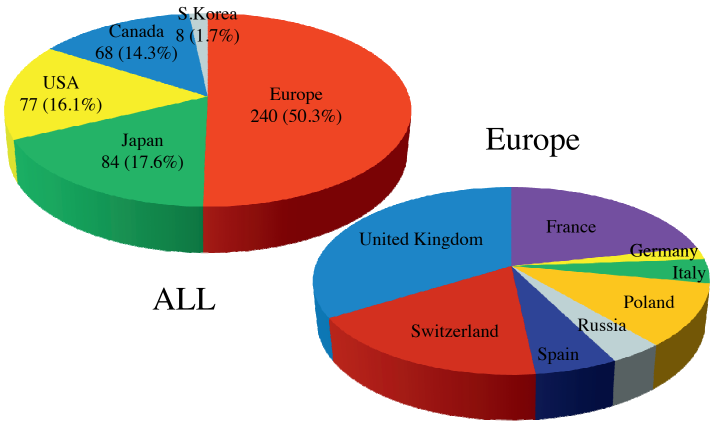


Fig. 5: Participants for T2K

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

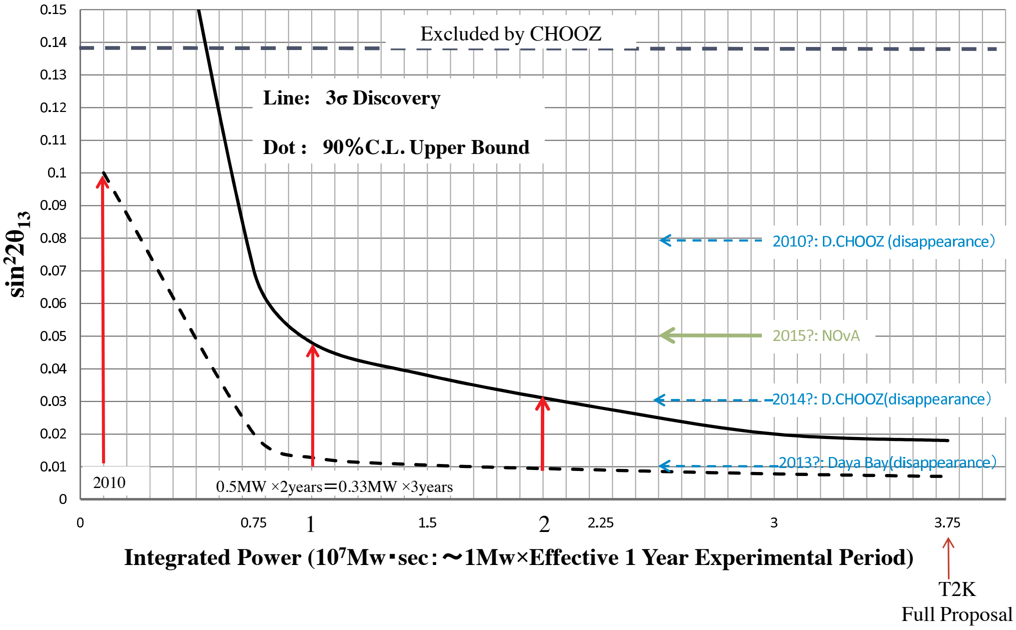


Fig. 6: T2K dicovery potential on $\nu_\mu \rightarrow \nu_e$ as a function of integrated proton power on target

- 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 $\rightarrow \nu$ K$^+$ and p $\rightarrow$ 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 $\nu_\mu \rightarrow \nu_e$ 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

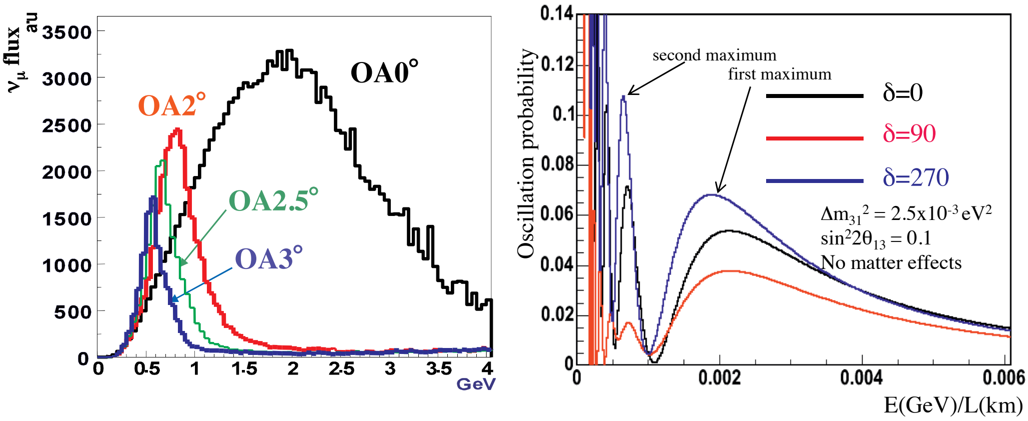


Fig. 7: Neutrino flux for various off-axis angle (left) and Probability for $\nu_\mu \to \nu_e$ oscillations as a function of the E(GeV)/L(km) for various δ. (right)

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.

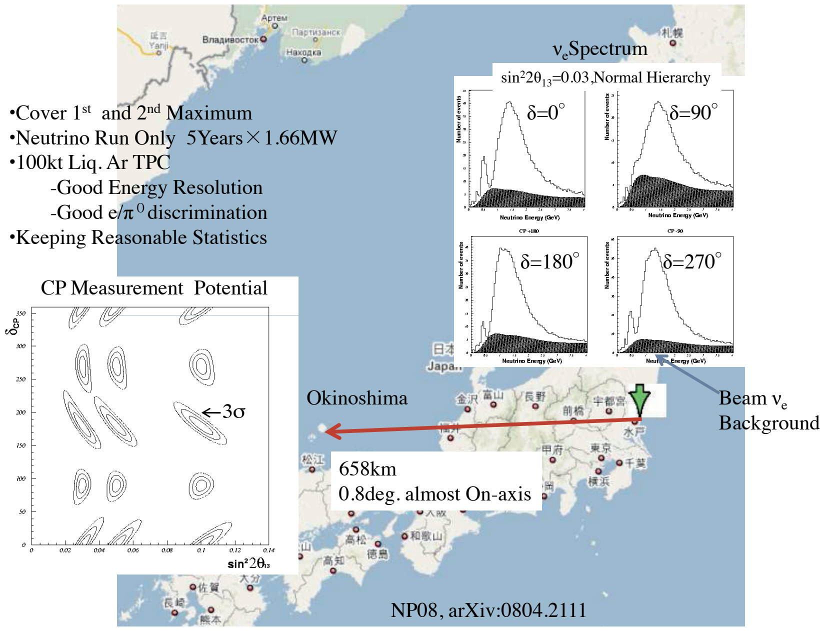


Fig. 8: Scenario 1: J-PARC to Okinoshima Long Baseline Neutrino Experiment

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.

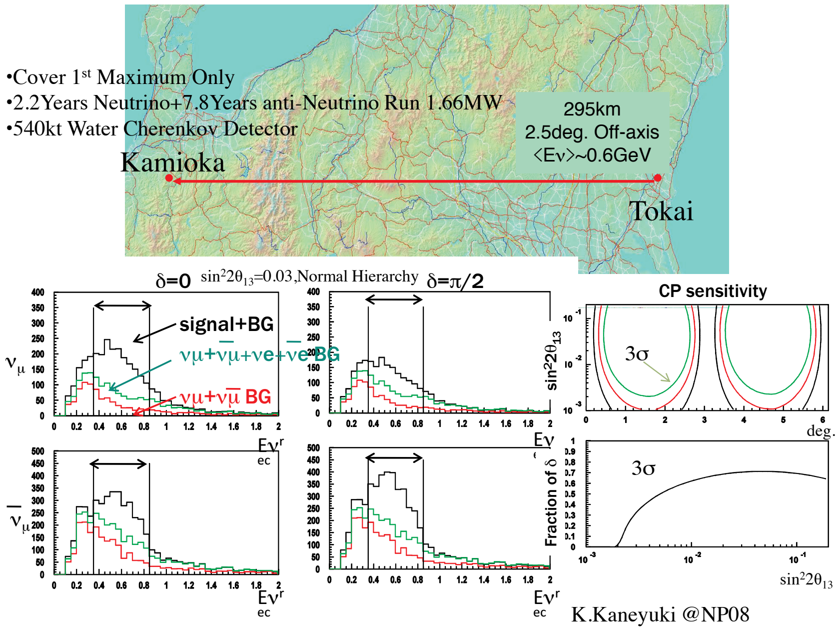


Fig. 9: Scenario 2: J-PARC to Kamioka Long Baseline Neutrino Experiment

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

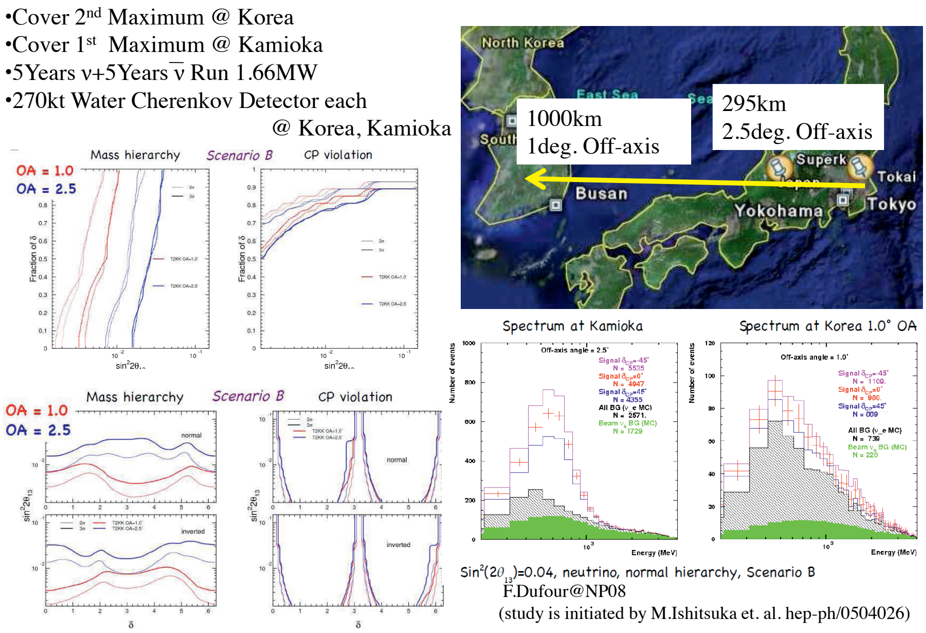


Fig. 10: Scenario 3: J-PARC to Kamioka and Korea Long Baseline Neutrino Experiment

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"

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Plans for Neutrino Super Beams in Europe

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Abstract
Neutrino Super Beams use conventional techniques to increase the neutrino beam intensity compared to the present neutrino facilities. The first part of these facilities consists of an intense proton driver producing a beam higher than a MW power. The protons hit a target able to afford the high proton beam intensity. The produced charged particles are focused by a system of magnetic horns towards the experiment detectors. The main challenge of these projects is to produce elements able to resist to the high beam intensity for many years. New high power neutrino facilities could be build at CERN profiting from the LHC upgrades. For this reason, the initial design of these upgrades has to include the possibility to go to high power facilities.

1 Introduction

The next generation of neutrino oscillation facilities will mainly have to observe the $\nu_1 \rightarrow \nu_3$ oscillation, measure the related θ_{13} angle and observe CP violation in the leptonic sector. According to the amplitude of θ_{13}, the future facilities will accurately measure these parameters or just make discoveries.

First hints of large θ_{13} value have started appearing ([1–5]) giving $\sin^2 2\theta_{13} \sim 0.08$ with large uncertainty. If this value is of this order of magnitude, the new reactor experiments under preparation (Double Chooz, Daya Bay and RENO) and T2K will be in good position to discover this remaining oscillation during the next 2–3 years. In this case, the Super Beam projects will have the opportunity, not only to observe this phenomenon, but also observe for the first time CP violation in the leptonic sector and make precise measurements.

The starting point of a Super Beam is a proton driver providing the necessary power to produce intense neutrino beams allowing the execution of the physics program in a reasonable time (below 10 years) and in a cost effective way (below 1 billion euros including the detector cost). To keep the cost low, the European projects propose to use already existing installations or use installations which will be built for high priority projects as LHC upgrades.

Important decisions are expected in 2012–2013 concerning the next accelerator facilities when convincing results will be obtained by the LHC experiments and when the $\sin^2 2\theta_{13}$ limit will go down at the level of 10^{-2}.

2 The CERN acceleration upgrade program

Since few years, CERN has launched studies on replacement or upgrade of its machines composing its present acceleration complex [6]. The aim of these modifications is first of all to increase the reliability of the present system (the present CERN accelerators are very old) and prepare the upgrades needed by the SLHC. To increase the brightness of the beam in the LHC to allow for phase 2 of the LHC upgrade, an increase of the injection energy in the synchrotrons is needed.

Fig. 1 summarizes the CERN acceleration system under study. With injection at 160 MeV from the new Linac4 (under construction), the PSB will be able to deliver a beam with twice the brightness. To improve the situation in the SPS, the new PS2 (supposed to replace the PS) will provide a proton beam of 50 GeV. The size of a 50 GeV synchrotron and the requirements to reliably cope with the maximum brightness ever necessary for the SLHC, led to an injection energy of $\sim$ 4 GeV. For this

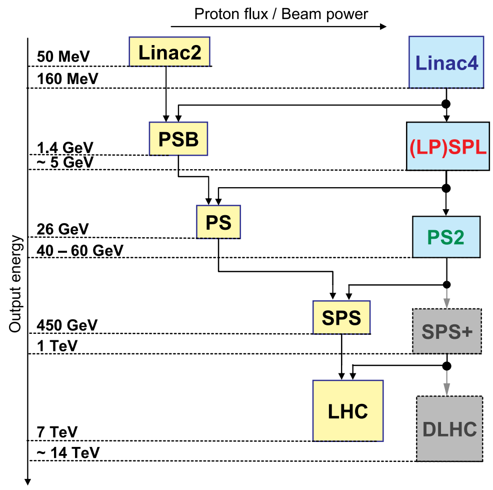

Fig. 1: Present (left) and possible new (right) CERN acceleration system.

injector, a superconducting proton linac (SPL [7]) has been chosen presenting significant advantages in the CERN context, especially because of its flexibility and its capability to evolve towards the very large beam power expected by, e.g., the future neutrino facilities [8]. This potential possibility is the decisive argument in favour of a linac–based PS2 injector with respect to an RCS–based solution.

3 High intensity neutrino beam using the CNGS

Before investigating about new facilities, an upgrade of the CNGS [9] has been studied in the framework of the MODULAr proposal [10]. This project proposes to use a 20 kton LAr TPC as a first step located at 10 km off–axis of the present LNGS underground laboratory and use a part of the existing CNGS installations. Two options are considered, one with a shallow detector just dedicated to the neutrino beam physics program and a second one in 1200 mwe depth in order to add to the physics program proton decay and cosmic neutrino searches.

For this project, a significantly higher intensity CNGS beam is needed compared to the present one. A study done by CERN [11] has shown that the maximum achievable intensity which could be reached after the upgrade of the whole CERN accelerator complex (future injectors, new SPS RF system, new CNGS equipment design) corresponds to 24.5×10^{19} p.o.t. for 200 days of operation with 80% SPS machine availability. In this study it is assumed that the present CNGS facility with small improvements can reach between 5×10^{19} p.o.t. (45% SPS availability) and 9.4×10^{19} p.o.t. (85% SPS availability).

For MODULAr project, the CNGS target and horns have to be redesigned. Fig. 2 presents the optimal neutrino spectrum calculated with new optics (SPS at 400 GeV). This spectrum is very similar to the one expected for NOVA project (NUMI at 120 GeV). Fig. 3 presents the MODULAr performance concerning $\sin^2 2\theta_{13}$ for a CNGS intensity of 1.2×10^{20} p.o.t./year (half of the theoretical CNGS maximum limit) and of 4.3×10^{20} p.o.t./year (nearly two times more than the theoretical CNGS maximum limit) compared with NOVA and T2K (phase 1). It has to be mentioned that the CNGS has been designed for a nominal value of 4.5×10^{19} p.o.t. never reached up to now. In 2008, the CNGS has delivered for OPERA experiment 1.8×10^{19} p.o.t. while it is expected for this year to deliver about 3.3×10^{19} p.o.t. (well below the assumed values of 5×10^{19} p.o.t. and 9.4×10^{19} p.o.t. mentioned above for the present CNGS performance). Thus, the missing intensity factor to reach the MODULAr requirements could be larger than the theoretical one.

In the CERN report [11], serious warnings are expressed concerning the possibility to replace CNGS elements (like the target and horn) after the present CNGS program has finished due to activation, not only of the target and horns, but also of the surrounding shielding. It has to be mentioned that, in

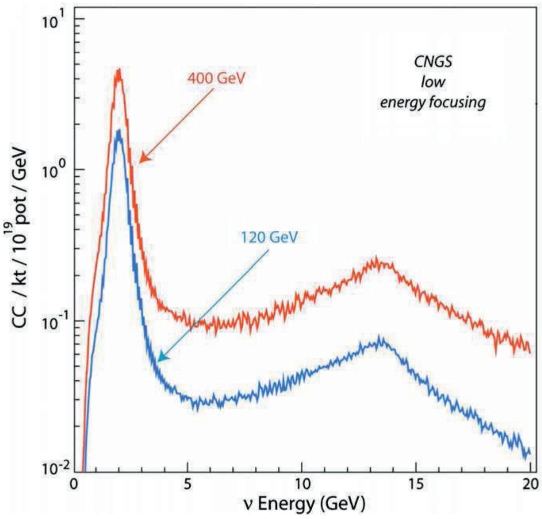

Fig. 2: Neutrino fluence for MODULAr (CNGS, 400 GeV) compared to the NOVA one (NUMI, 120 GeV).

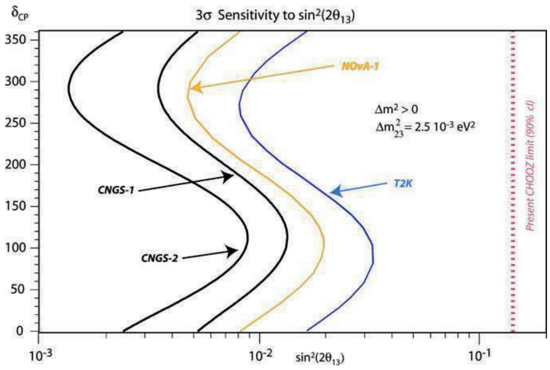

Fig. 3: MODULAr 3 σ sensitivity to $\sin^2 2\theta_{13}$ versus δ_{CP} for 1.2×10^{20} p.o.t./year (CNGS-1) and 4.3×10^{20} p.o.t./year (CNGS-2), compared to NOVA and T2K performance.

order to avoid these kind of problems and keep full upgradability, the T2K beam facility has anticipated and has built since the beginning the target station, the decay tunnel as well as the beam dump, in a way to be able to go up to 4 MW proton beam while the announced present goal is to go up to 1.66 MW.

4 High intensity neutrino beam using the PS2

Very recently, the utilization of PS2 to provide protons for a neutrino beam has been investigated in the framework of the European FP7 LAGUNA project [12, 13]. Fig. 4 presents the performance of such a project in the case where a 100 km LAr detector is placed in Pyhäsalmi mine in Finland ($0.25°$ off–axis, 2300 km from CERN, $2\nu + 8\bar{\nu}$ years).

For this study, a 50 GeV PS2 proton beam is considered with a beam power of 1.6 MW (360×10^{19} p.o.t./year). The result is promising but, according to CERN studies [14], the maximum PS2 achievable power, expected by the present design, is of the order of 0.32 MW, well below the power considered in the above studies. Moreover, for such utilization, the whole PS2 facility has to be built since the beginning taking into account the high power possibility.

5 High Power SPL

The possibility of constructing a High Power SPL to satisfy, not only the SLHC requirements, but also to provide protons to a neutrino facility, has been studied in [15] for a 2.2 GeV protons and [16] for an increased energy option of 3.5 GeV. Table 1 summarizes the main required characteristics of a High Power SPL (HP–SPL) for a Super Beam compared to the SLHC requirements (LP–SPL). The main difference between the two options, LP–SPL and HP–SPL, is the significant proton beam power and repetition frequency increase.

The necessary modifications to go from the low power to high power are given in [17]. Here, we insist on the possibility to foresee in the initial SPL design (to be decided around 2012) the high power option (especially concerning the radiation shielding around the facility) as it is already done for the Linac4 which is now under construction. This will avoid upgradability problems in the future as those mentioned before for the CNGS facility.

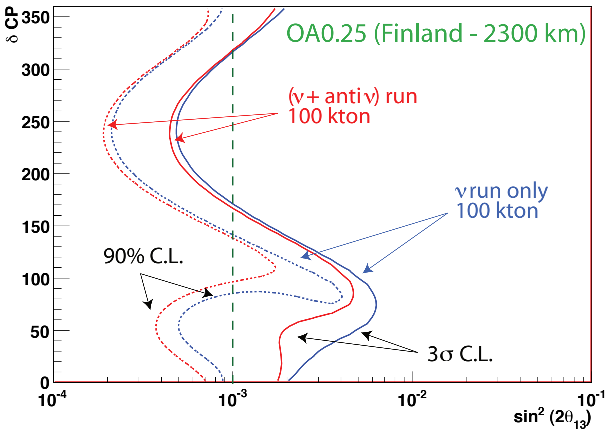

Fig. 4: Physics performance obtained using a high intensity PS2 proton beam and an off–axis detector placed in a distance of 2300 km and a 100 kton LAr detector.

Table 1: Low and High Power SPL characteristics for the SLHC (LP–SPL) and the Super Beam (HP–SPL) needs.

parameter	LP–SPL	HP–SPL
Kinetic Energy (GeV)	4	~ 4
Beam power (MW)	0.12	4 MW
Repetition frequency (Hz)	0.6	50
Protons/pulse ($\times 10^{14}$)	1.1	1
Av. pulse current (mA)	20	40
Pulse length (μs)	900	5

5.1 CERN to Fréjus Project (C2F)

The utilization of the SPL to produce a neutrino beam oriented towards the Fréjus tunnel has been investigated at the beginning of this decade [18] considered as the first stage of the Neutrino Factory complex.

Conventional muon neutrino beams are produced by the decay of mesons (pions and kaons). These mesons are produced by colliding a proton beam with a target. To send the neutrinos in the right direction, the only available possibility is to act on the direction of the charged mother particles. After the proton collision with the target, the emerging mesons are collected and focused towards the neutrino detector using a sign–selecting toroidal magnetic field. The hadron collector used very often in these applications is a magnetic horn pulsed with a very high electrical current.

In the case of the CERN SPL Super-Beam (SPL–SB) the operation conditions will be much more severe than in previous applications. Table 2 shows a comparison of some horns already used by past or ongoing projects. In this table one can see that the under investigation horn has a small length which could be an advantage during the fabrication and operation. But, on the other side, the proton driver power (4 MW) and repetition rate (50 Hz) are considerably higher than other applications inducing severe operation conditions.

An initial design of a horn prototype system (horn+reflector) foreseen for the Neutrino Factory has been made at CERN for a 2.2 GeV proton beam [19, 20]. An optimization and a redesign has been made in a Super Beam context [21, 22] driven by the physics case of a long baseline experiment (130 km) between CERN and Fréjus (MEMPHYS detector location [28]). From these studies, it came out that the optimal proton energy was between 3.5 and 4.5 GeV. Above these energies, the muon neutrino beam starts being contaminated by electron neutrinos mainly coming from kaon decays.

Both studies concluded that the proton target has to be installed inside the horn to maximize the

Table 2: Comparison of horns already used or under utilization with the SPL–SB proposed one.

Project	Proton Energy (GeV)	Power (MW)	Rep. Rate (Hz)	Current (kA)	Number of horns	Length (m)
CNGS	400	0.2	2 pulses/6 sec	150	2	6.5
K2K	12	0.0052	0.5	250	2	2.4–2.7
NUMI	120	0.4	0.5	200	2	3
MiniBoone	8	0.04	5	170	1	1.7
T2K	50	0.75	0.3	320	3	1.4–2.5
SPL-SB	3.5-5	4	50	300–600	2	1.5

hadron collection (Fig. 5). For the power dissipation of the system, this condition (imposed by the relatively low proton energy and the consequently low forward hadron boost) is a very sever constraint. Sever conditions will also be met by the target station and the target itself.

In the previous studies, a liquid mercury target 30 cm long has been considered as the one proposed for the Neutrino Factory. But, it has been shown (MERIT project [23]) that to maintain the liquid mercury jet integrity, the presence of a magnetic field higher than 10 T is necessary. This condition is only satisfied by the Neutrino Factory operation conditions where a solenoid is used as hadron collector, but not in the case of a magnetic horn where the magnetic field is confined inside the horn. Moreover, mercury is not compatible with aluminum alloys usually used in the horn manufacturing.

The main advantage of a liquid target is the power dissipation easily done by the liquid recirculation. A solid target utilization doesn't seem compatible with the very high power (4 MW) proton beam. Studies already done show that with the present knowledge, solid targets (e.g., graphite) can only afford proton beams up to 1.5 MW. Mainly for all these reasons, the target/horn integration has to be seriously studied since the beginning of the design.

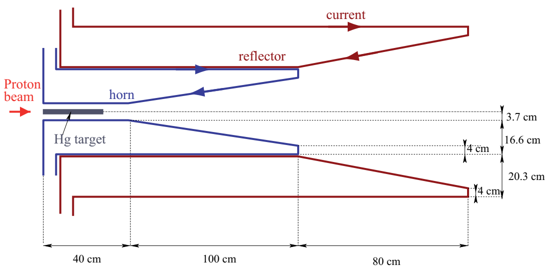

Fig. 5: Schematic view of the horn and reflector optimized for a 3.5 GeV SPL proton beam.

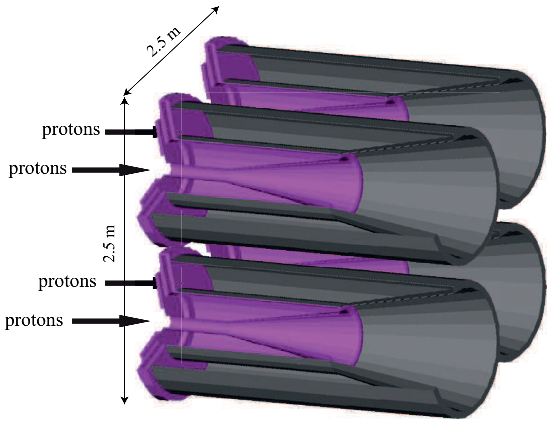

Fig. 6: Schematic view of 4 target/horn systems sharing the proton beam power.

5.2 Target/horn system

In the Super Beam baseline option of the project, the pions are produced by the impact of a primary 4 MW/3.5 GeV pulsed proton beam on a target located inside the horn (Fig. 5).

The magnetic horn under study will have to focus hadrons (mainly pions) with a mean momentum of 600 MeV/c parallel to the beam axis and towards a distant detector. The horn is composed of an aluminum as thin as possible skin (<3 mm) to minimize the energy deposition by the particles coming out of the target. To obtain the toroidal magnetic field needed for the hadron focusing, a high current circulates between the internal and external skins inducing inside the horn a magnetic field varying like $1/r$ where r is the distance from the horn axis. In this way, the magnetic field outside the horn completely vanishes in order the particles coming out to suitably stop spiring at the moment where their direction is parallel to the horn axis. The electrical current required to efficiently focus the hadrons is of the order of 300 kA for the horn and 600 kA for the reflector enveloping the horn.

The horn is submitted to a strong electromagnetic pulse producing thermo–mechanical stresses, vibrations, and fatigue reducing its lifetime. The current is brought from the pulse generator up to the horn using strip lines to avoid heating. These strip lines have to be well studied, especially their different connections to avoid breaking due to vibrations induced by the 50 Hz pulses. This project will benefit from the experience of the CERN prototype horn designed for 2.2 GeV proton beam, CNGS, Miniboone, and T2K horns.

The horn shape strongly depends on the hadron energy and thus on the primary proton beam energy. Since the first CERN design, the physics requirements have changed according to recent physics results leading to the actual required proton energy which is of the order of 4 GeV (matching the PS2 injection requirements) instead of 2.2 GeV. Mainly for this reason and to profit from new technological developments, a new horn design has to be done and a prototype has to be constracted again. An optimized horn design maximizing the neutrino beam intensity could improve the physics results.

Due to the very sever operation conditions, the whole system's integration including the target, the horn and the cooling system, has to be carefully studied. As mentioned before, with the present knowledge, it is impossible to use a solid target with a proton driver power higher than 1.5 MeV. In order to mitigate the high power beam effect, one could use 4 target/horn systems as depicted by Fig. 6 [25]. This takes advantage of the small horn size and from the reduced length of the hadron decay tunnel (~ 50 m) just after the horn which diameter can be increased to satisfy the 4 horn system. In this case, the proton beam power for each target/horn system is reduced to 1 MW. This scheme presents many advantages as less exposure to radiation and easier power dissipation. The main disadvantage comes from the beam sharing. To send the proton beam in the 4 systems, 4 proton lines will be needed (pulsed simultaneously or one after the other). These 4 beam lines will add an extra cost to the proton beam facility. To avoid this problem one could envisage a rotating 4 target/horn system as the one of Fig. 6 or a more linear translating system where the target/horn systems are on a straight line. In these last 2 cases, it is not any more needed to increase the diameter of the decay tunnel.

Concerning the target, other possibilities are under investigation as a fluidized jet of tungsten or tantalum particles in helium gas [26]. Flowing powder targets have the advantages of fluid targets without presenting the disadvantages of solid targets. The deposited power is easily dissipated due to the recirculation. They don't break because the shock waves are constrained within the material grains.

A tuning of the multiphysics simulations of the target/horn system (fatigue, deformations, modal analyses, transient thermo mechanical excitation of the structure, skin effect and Joule heating, power dissipation, heat exchange and cooling, radiation resistance, etc.) could be done using input provided by the previously mentioned facilities (mainly T2K phase 2 where a 1.66 MW proton beam will be used). To validate these simulations, some tests and R&D will be necessary (target irradiations, horn pulsing etc.) where CERN could play a leading role. These studies have also to include the design of a complete remote handling installation for the horn and target maintenance and possible exchange.

To reduce the length of the proton pulse from 0.57 ms (delivered by the SPL) to few μs (affordable by the current pulse duration sent to the horn), after the proton driver, a beam accumulator is normally needed but not a compressor as in the case of the Neutrino Factory [16].

The European FP7 Design Study EUROν [24] studies all aspects of feasibility of the target, horn and integration of the two objects.

5.3 Physics Performance

This facility gives promising results especially for relatively high θ_{13} values as those extracted by the combination of all experimental results [1–4] including very recently the latest SNO results [5]. In [21] is described the possibility to use a 3.5 GeV proton beam and a 440 kton Water Čerenkov detector located at Fréjus tunnel (130 km distance corresponding to the 1st oscillation maximum). Fig. 7 presents the neutrino and anti–neutrino expected spectra, while Fig. 8 gives the $\sin^2 2\theta_{13}$ sensitivity versus δ_{CP} compared to the T2HK one. One can see that this project could be sensitive to $\sin^2 2\theta_{13}$ for values lower than 10^{-3}.

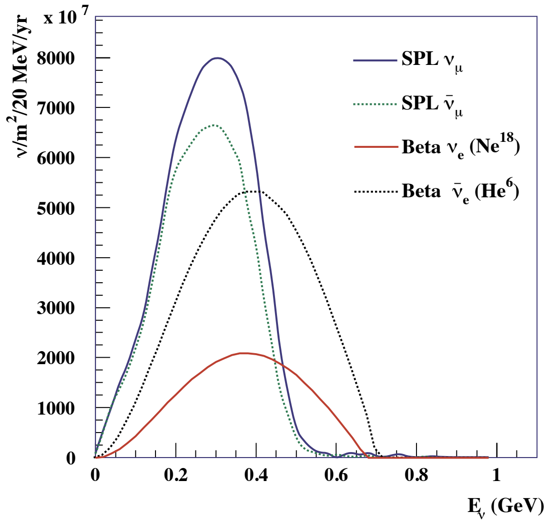

Fig. 7: Neutrino spectra for SPL Super Beam and CERN Beta Beam.

A very good synergy exists between this project and the CERN Beta Beam one ($\gamma \sim 100$) providing neutrinos of similar energy ($\sim$300 MeV) than those produced by the SPL Super Beam project (Fig. 7). The two projects could share the same detector placed at Fréjus tunnel. The combination of the results of both experiments (Fig. 8) increases considerably the physics performance of the whole project. This combination also allows to test separately CP, T, and CPT violation by two different ways using the oscillations $\nu_\mu \to \nu_e$, $\bar{\nu_\mu} \to \bar{\nu_e}$, $\nu_e \to \nu_\mu$ and $\bar{\nu_e} \to \bar{\nu_\mu}$.

On top of that, the unoscillated neutrino beam of each facility would allow to measure the neutrino interaction cross–section of the other facility reducing significantly the systematic errors. The weak point of both facilities is the short baseline distance reducing considerably the possibility to observe matter effects and thus give information on mass hierarchy. Fig. 9 gives the sensitivity to this last parameter versus δ_{CP} (dotted lines). This sensitivity is significantly improved for all projects when combined with the accumulated atmospheric neutrino data (solid lines) in a way to be able to observe a 2σ effect for $\sin^2 2\theta_{13} > 0.02$.

Another possibility expressed recently improving much more the physics performance of this project is to send a Beta Beam to Fréjus detector ($\gamma \sim 500$, $d = 960$ km) from DESY using HERA to accelerate the radioactive ions [30].

The large Water Čerenkov detector MEMPHYS can also be used to study the proton lifetime and detect cosmological neutrinos (supernovae, solar, atmospheric) and geoneutrinos. All these possibilities are studied by LAGUNA. MEMPHYS can profit from the excavation of a safety gallery (under construction) to avoid any interference during installation and operation of the detector with the car traffic in the highway tunnel.

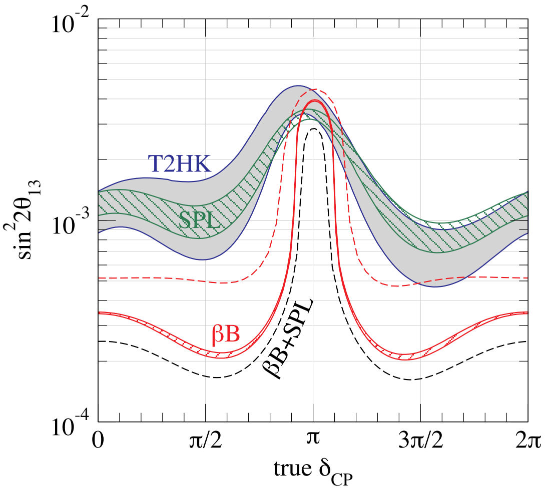

Fig. 8: 3 σ discovery sensitivity to $\sin^2 2\theta_{13}$ for SPL Super Beam, Beta Beam and T2HK as a function of the true value of δ_{CP} for $(5\nu + 5\bar{\nu})$ years running period for Beta Beam and $(2\nu + 8\bar{\nu})$ years for SPL Super Beam and T2HK.

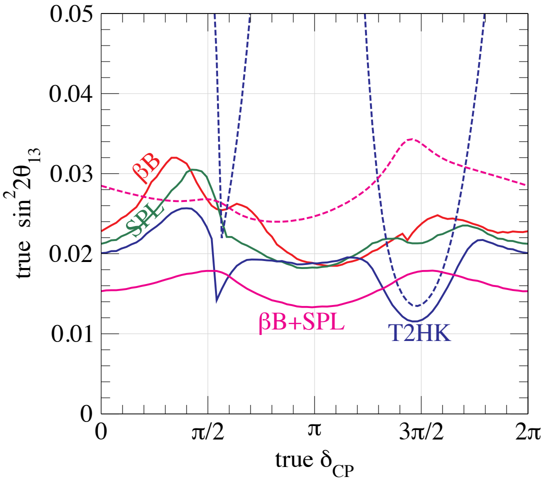

Fig. 9: Sensitivity to the mass hierarchy at 2 σ as a function of the true values of $\sin^2 2\theta_{13}$ and δ_{CP} without (dotted lines) and with (solid lines) combination with atmospheric neutrino measurements.

5.4 New Studies

New studies on SPL Super Beam have been started in the EUROν framework in order to optimize the physics performance of the project.

In these new studies, the possibility to use a liquid mercury target has been abandoned for the reasons already explained. A carbon target combined with a MiniBooNE like horn (Fig. 10) has been considered [29]. The length of the carbon target has been increased (78 cm) compared to the mercury one (30 cm) previously considered in order to have the equivalent of 2 interaction lengths in both cases.

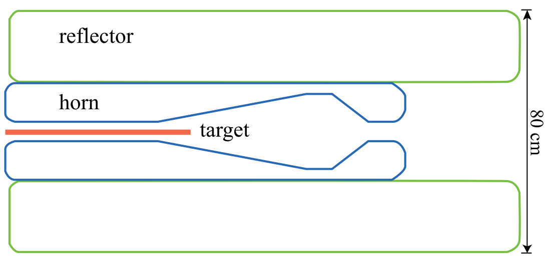

Fig. 10: New horn design using carbon target.

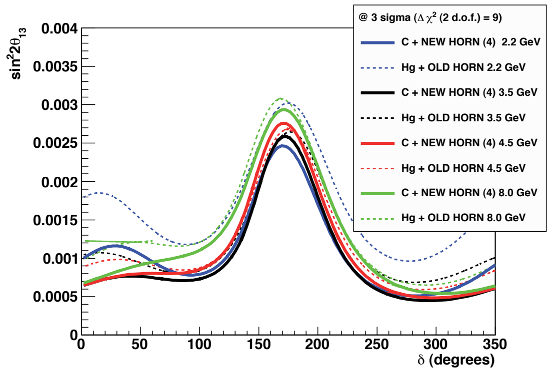

Fig. 11: $\sin^2 2\theta_{13}$ sensitivity with new horn versus δ_{CP} for different targets, mercury (30 cm) and carbon (78 cm).

The very first results are very promising demonstrating that there is still room for improvement by just optimizing the horn system. Fig. 11 shows a comparison between all already studied options (mercury, carbon) for several proton driver energies (2.2, 3.5, 4.5 and 8 GeV). The best performance is obtained with the new horn for 3.5 GeV proton energy. On top of the much easier handling, the utilization of a carbon target compared to the mercury one reduces the neutron flux by a factor of 15 decreasing significantly the risk of radiation damages.

6 Conclusions

The possibilities of constructing conventional high intensity neutrino beams in Europe are mainly concentrated around CERN.

The option of increasing the performance of existing facilities like the CNGS is very limited, mainly compromised by the fact that during the construction the passage to high power facility has not been foreseen. Also, the required intensity seems not to be reachable without major investment.

The upgrade of the CERN accelerator complex, mainly to satisfy the SLHC requirements, is very expected by the european neutrino community. These new facilities could provide high power proton beams which could be used to produce high intensity neutrino beams.

The present design of the PS2, suppose to replace the PS, could give a neutrino beam with an intensity of at least 4 times lower than the required one to be competitive. The High Power SPL could provide more than 4 MW proton beam opening new possibilities for low energy neutrino beams. This will give the possibility to observe for the first time CP violation in the leptonic sector. This facility has a big synergy with the CERN and DESY Beta Beam projects.

The european EUROν Design Study finishing in 2012 will study and compare (physics performance, technological risks, cost, timescale) the main european facility proposals, while the second european Design Study LAGUNA finishing next year, studies and compares the detection technics and underground possible sites to host large neutrino detectors.

In 2012–2013 the particle physics community will be ready to take decisions about the construction of new facilities mainly those concerning the LHC upgrade. It is important at that time to preserve the possibility of upgrading these new installations to high power facilities mainly to produce high intensity neutrino beams.

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