Neutrino detectors for oscillation experiments

Y. Kudenko

Institute for Nuclear Research of RAS,
60 October Revolution Pr 7a, Moscow, Russia
Moscow Institute of Physics and Technology,
Institutskiy per. 9, Dolgoprudny, Moscow Region, Russia
Moscow Engineering Physics Institute,
Kashirskoe shosse 31, Moscow, Russia

E-mail: kudenko@inr.ru

Abstract: A brief overview of the development of neutrino detectors for long-baseline oscillation experiments at accelerators and reactors is presented. Basic principles and main features of detectors of running accelerator experiments T2K and NOνA sensitive to a first level of CP violation and neutrino mass hierarchy, and reactor experiments Daya Bay, RENO and Double Chooz which measured the mixing angle $\theta_{13}$ are discussed. A variety of different experimental techniques is proposed and developed for the next generation oscillation experiments: a 20 kt scintillator detector for the reactor experiment JUNO, a 0.52 kt water-Cherenkov detector Hyper-Kamiokande, and a massive liquid argon time-projection chamber neutrino detector envisaged for the DUNE experiment. Present status of these detectors, recent progress in R&D and future prospects are summarized in this paper.

Keywords: Cherenkov detectors; Neutrino detectors; Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others); Time projection chambers

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1 Introduction

The discovery of neutrino oscillations has provided convincing evidence for non-zero neutrino masses and leptonic mixing. This phenomenon is the first clear example of new physics beyond the Standard Model (SM). Oscillation probabilities between the three active neutrinos are described by six independent parameters: 3 mixing angles $\theta_{12}$, $\theta_{23}$, and $\theta_{13}$, two neutrino mass-squared differences $\Delta m_{21}^2 = m_2^2 - m_1^2$, $\Delta m_{32}^2 = m_3^2 - m_2^2$, and possibly one complex CP violating phase $\delta_{CP}$. These parameters are determined in oscillation experiments with atmospheric, solar, reactor and accelerator neutrinos, except for $\delta_{CP}$ and the sign of $m_{32}^2$. Both the normal mass hierarchy ($m_3 \gg m_2 > m_1$) and inverted hierarchy ($m_2 > m_1 \gg m_3$) are possible. The science program of current and future long baseline accelerator and reactor experiments is focused on a search of CP violation in leptonic sector and measurement of $\delta_{CP}$, determination of neutrino mass hierarchy, and precision measurements of mixing parameters. The concepts of these experiments as well as various detector techniques will be described below.

2 Current experiments

2.1 T2K

The T2K (Tokai-to-Kamioka) experiment [1] uses a high intensity off-axis neutrino beam produced by 30 GeV protons at J-PARC (Japan Proton Accelarator Research Complex). The far detector, Super-Kamiokande, a well known 50 kt Cherenkov detector located at a distance of 295 km from J-PARC, measures the spectra of muon and electron neutrinos (antineutrinos) after oscillations. Super-Kamiokande distinguishes muon and electron from neutrino charged current interactions.
using the shape of the Cherenkov ring. The reconstruction of the neutrino energy is made with lepton kinematics assuming a charged-current quasi-elastic scattering, in which a neutrino is converted to a charged lepton in the reaction $\nu_l + n \rightarrow l^- + p$. The T2K 2.5° off-axis beam has a relatively narrow band neutrino (antineutrino) flux with a peak energy of 0.6 GeV, which corresponds to the first oscillation maximum at Super-Kamiokande. The T2K near detector complex located at 280 m from the pion production target consists of an on-axis detector (INGRID) and a set of multiple sub-detectors (ND280) placed at the angle of 2.5° relative to the proton beam direction inside the UA1 magnet operated with a magnetic field of 0.2 T. The near detectors are designed to characterize the parameters of the unoscillated neutrino beam and neutrino cross sections. The tracker consists of two fine-grained detectors (FGDs) and three time projection chambers (TPCs) and provides the primary input data in the current T2K oscillation analyses. Both FGDs (the first detector is comprised of scintillator bars, the second detector consists of scintillator bars and water layers) are utilized as a neutrino target. Three TPCs are used to measure the momenta and the sign of charged particles. The neutrino flux and cross-section models are constrained using data collected in ND280.

The T2K Collaboration has successfully applied a method of fitting the near detector data with parametrized models of the neutrino flux and interaction cross sections and reduced the systematic uncertainties on the predicted rate of $\nu_\mu$ and $\nu_e$ at SK to a 6–7% level [2]. However, there are several limitations to this approach. In the T2K experiment, water is used as the neutrino target in SK. But the mass fraction of water of the second FGD is only 47%. The ND280 detector has a low efficiency for large angle tracks while Super-Kamiokande has a 4\pi angular acceptance. The uncertainty of the neutrino cross section on water due to this difference is one of the major systematic errors in the T2K neutrino oscillation analysis. To measure neutrino (and antineutrino) cross sections on water and hydrocarbon with high precision and large angular acceptance a new neutrino detector, WAGASCI (WAter Grid And SCIntillator) has been developed [3]. The goal of this experiment is to measure the ratio of neutrino cross sections on plastic and water with a 3% accuracy at the neutrino energies $\leq 1$ GeV. The WAGASCI experiment will utilize the detector which comprises a segmented target of water and scintillator cells, muon range detectors, and a magnetic spectrometer to measure momentum and charge identification of the outgoing muons from charged current interactions. Figure 1 shows the layout of the WAGASCI set-up, with the active neutrino target WAGASCI in the center, the Magnetized Iron Neutrino Detector (Baby-MIND) [4], and two side Muon Range Detectors (MRDs). The central neutrino interaction target consists of 4 blocks, each $1 \times 1 \times 0.5$ m$^3$, with an alternating pattern along the beam direction between water-filled and hydrocarbon-filled blocks instrumented with plastic scintillator detectors, as shown in figure 2. These detectors will be read out with arrays of 32 channel Multi Pixel Photon Counters (MPPCs). MRDs which measure the momentum of muons by range consist of several plates of steel each of 3-cm thick, interleaved with plastic scintillator detector modules. The Baby-MIND detector consists of 33 magnetized 3-cm steel plates which provide a magnetic field of 1.5 T and 18 scintillator modules that measure the position of hits along the spectrometer and the curvature of the track in the magnetic field. Detector modules consist of x-y planes of plastic scintillator bars (figure 2), with wavelength shifting fibers read out with single MPPCs. The WAGASCI detector is expected to be commissioned and start data taking in the beginning of 2018.
2.2 NOνA

The NOνA (NuMI Off-axis νe Appearance) experiment [5] is designed to study neutrino oscillations using Fermilab’s NuMI neutrino beam. The results obtained in this experiment are consistent with the T2K νe appearance measurements and confirmed obtained in T2K constraints on possible δCP with a preference for δCP ≃ −π/2. NOνA has a long baseline of 810km that leads to better sensitivity of mass hierarchy. NOνA uses two neutrino detectors: a 300t near detector located
approximately 1000 meters downstream of the pion production target and 100 m underground, and a 14 kt far detector is situated on the surface of the earth in Ash River, Minnesota. Both liquid scintillator-based detectors with identical structures (figure 3) are located at the angle of 14.6 mrad from the central axis of the NuMI beam. The neutrino beam with a narrow energy interval centered at 2 GeV is tuned to the first oscillation maximum with “atmospheric” oscillation parameters. The NOνA detectors are highly segmented tracking calorimeters. The segmentation is provided by a lattice of extruded polyvinyl chloride (PVC) cells with a cross section of $6.6 \times 3.9 \text{ cm}^2$. The cells are ~15 m long in the far detector and ~4 m long in the near detector. Each scintillator-filled PVC cell is equipped with a WLS Y11 fiber looped at the far end of the cell. Both near ends of the WLS fiber terminate on the same pixel of a 32-pixel avalanche photodiode (APD). The far detector has about $3.5 \times 10^5$ PVC cells. Approximately 37% of the detector mass is in the PVC structure and 63% of the mass is in the liquid scintillator. The radiation length of the detectors (38 cm) is much larger than the cell dimensions. The geometry of NOνA detectors allows to provide good reconstruction and separation of electromagnetic and hadronic showers, identification of muons and neutral pions. The experiment is taking data with the beam power of 700 kW and an exposure of $36 \times 10^{20}$ protons on target is expected to be delivered by 2023.

2.3 Reactor experiments

The main goal of three running reactor experiments Daya Bay [6] in China, RENO [7] in Korea, and Double Chooz [8] in France is the precise measurement of the third mixing angle $\theta_{13}$. To accomplish the task, these experiments use a near-far detector conception in that a near detector is located close to a reactor where the oscillation due to $\theta_{13}$ is small and a far detector is installed at ~1 km from the reactor, an optimal distance to provide a good sensitivity to $\theta_{13}$. All neutrino detectors in these experiments use a liquid scintillator doped with gadolinium. Since both detectors have identical structure, the systematic uncertainties of neutrino flux, neutrino cross section, detection efficiency,
and detector mass are significantly suppressed. The experiments use the inverse beta decay to detect reactor antineutrinos in a liquid scintillator

$$\bar{\nu}_e + p \rightarrow e^+ + n.$$  \hfill (2.1)

The cross section of this process is very well known. The positron deposits energy in the scintillator, which is converted in scintillation light. The positron then annihilates with an electron with a contribution 1.02 MeV to its kinetic energy. The energy of the detected reactor antineutrino can be obtained from the energy of the positron signal $E_{\bar{\nu}_e} = E_{e^+} + 0.8$ MeV. The neutron quickly thermalizes and is absorbed by Gd within tens $\mu$s. Then the exited Gd isotope emits photons with the total energy $\sim 8$ MeV. So the antineutrino signal is identified by the delayed coincidence of the positron signal and the Gd signal. RENO and Double Chooz use two detectors, one near and one far. The Daya Bay experiment has a more complex set-up: six nuclear reactors with a total power of 17 GWth (thermal power), four near detectors located in two places close to reactors, and four far detectors, each contains 20t of liquid scintillator. The energy resolution of $8%/\sqrt{E}\text{(MeV)}$ was obtained in Daya Bay detectors. The main oscillation result, the value of $\theta_{13}$ was obtained from the ratio of antineutrinos detected in the far and the near detectors. It is independent of the calculation of the antineutrino flux and the spectrum from the reactors. After a few years of data taking, Daya Bay have measured $\sin^2 2\theta_{13}$ with a very impressive precision of about 2.5%.

3 Future projects

3.1 JUNO

The Jiangmen Underground Neutrino Observatory (JUNO) [9], a large liquid scintillator detector located at a 53 km distance from reactors, has a primary goal of the determination of the neutrino mass hierarchy. The detector will be located 1800 meters of water equivalent (m.w.e.) underground and consists of a 20 kiloton liquid scintillator (based on LAB doped with PPO and bis-MSB) contained in a huge 35.4 m diameter acrylic sphere (figure 4(a)), instrumented by more than 17000 20-inch and about 34000 3-inch PMTs. Small PMTs will be mounted in gaps between large phototubes, as shown in figure 4(b) ensuring a 77% photocathode coverage. It should be noted that the scintillator does not contain Gd in order to be more stable in time. To discriminate between the neutrino hierarchies at $\geq 3\sigma$, the energy resolution is required to be $3%/\sqrt{E}\text{(MeV)}$ and the absolute energy scale should be calibrated with a precision of 1%. To meet these criteria and provide a high light yield of $\sim 1200$ p.e./MeV, PMT’s should have a quantum efficiency $\geq 27\%$ and the attenuation length of the liquid scintillator should be longer than 20 m at 430 nm [10]. The antineutrino event will be identified observing the inverse beta decay (2.1) and the delayed signal of 2.2 MeV from the neutron captured by hydrogen within 200 $\mu$s. Two types of 20” PMTs will be utilized: superalkali Hamamatsu PMTs (figure 4(d)) and new MCP-PMTs (figure 4(c)) in which the dynode chain is replaced by micro channel plates. A new design of MCP-PMTs integrates two photocathodes, a transmission and reflective ones [11]. This approach allows to recover some nonconverted photons. Both PMT types reached the quantum efficiency more than 30% that is needed to obtain the required energy resolution. JUNO plans to start data taking in 2020.
3.2 Hyper-Kamiokande

The Hyper-Kamiokande detector (HK) [12], a proposed next-generation water-Cherenkov detector, will have a broad physics program which covers many areas of particle and astroparticle physics. It will serve as a far detector of a long-baseline neutrino experiment T2HK (Tokai-to-Hyper-Kamiokande) using neutrino and antineutrino beams produced at J-PARC upgraded to a ∼ 1 MW of power. The main goal of the T2HK experiment is the sensitive search for CP violation in neutrino oscillations [13], i.e. the observation of the CP violation with a significance of ≥ 5σ for about 60% of all values of δCP and the measurement of δCP with a precision of 7° for δCP = 0° or about 20° for δCP = −π/2 in 10 years of data taking. To achieve this goal the total systematic uncertainty on far detector rate prediction should be less than 3%. This issue can be addressed by the upgrade of ND280 and by building an intermediate water Cherenkov detector (see, for example [14]) at about 1 km from the T2K neutrino beam production target. Hyper-Kamiokande will also increase existing sensitivity to proton decay by an order of magnitude, and will study neutrinos from various sources, including atmospheric neutrinos, solar neutrinos, supernova neutrinos and annihilating dark matter. HK is based on the proven technology of the highly successful Super-Kamiokande detector. The HK detector (figure 5) will be located about 8 km south of Super-Kamiokande with an overburden of 1750 m.w.e. It will consist of two cylindrical tanks (each 60 m high and 74 m in diameter) and have a total (fiducial) mass of 0.52 (0.37) Mton, making it 10 (17) times larger than its predecessor Super-Kamiokande. It will use 40,000 PMTs per tank to reach the same 40% photocoverage. Similar to Super-Kamiokande, an outer detector with the layer width of 1–2 m will help to constrain the external background. In order to achieve broad scientific goals, particles with a wide range of energies should be reconstructed. The number of Cherenkov photons that hit each photosensor ranges from one to several hundred. Thus, the photosensors are required to have a
Figure 5. Schematic view of the Hyper-Kamiokande.

high photon detection efficiency, a wide dynamic range, and a good linearity. The location of the neutrino interaction vertex is reconstructed using the Cherenkov photon arrival timing information at each PMT. Therefore, good timing resolution of photosensors is essential, and the jitter of the transit time is required to be less than 3 ns ($1\sigma$) for a single photon. To meet these requirements, two types of new 50 cm diameter vacuum-based photodetectors have been developed for Hyper-Kamiokande. One is the Hamamatsu PMT R12860 with a box-and-line dynode, which has a faster time response and a better collection efficiency compared to Hamamatsu PMT R3600 that have been used successfully in Super-Kamiokande. The other is a hybrid photodetector, HPD, which uses an avalanche diode as an electron multiplier. Hamamatsu R12860 has a very good timing and charge resolutions for the single photon, ~ 1 ns and about 35%, respectively. An improved photocathode of R12860 allows to reach the quantum efficiency of 30% at 400 nm, about 1.4 times higher than that of the Super-Kamiokande PMTs, as shown in figure 6 (left), and the photoelectron collection efficiency of R12860 is also much higher. As a result, the total efficiency for the single photon detection of Hamamatsu R12860 is almost twice higher than that of the Super-Kamiokande PMTs, as shown in figure 6 (right). This newly developed high-efficiency and high-resolution PMTs met the requirements for the HK photosensor [16] and will significantly contribute to the main goal of the Hyper-Kamiokande experiment. It should be also mentioned that R12860 has an improved pressure tolerance so that a deeper tank becomes feasible. Alternative solutions for photosensors are also extensively studied by the international collaboration [16]. In case of approval, the construction of Hyper-Kamiokande can start in 2018 and data taking is expected to begin in 2026.
Figure 6. The quantum efficiency of Hamamatsu R12860 (left) and the single photon detection efficiency as a function of incident positions (right) of the new Hamamatsu PMT R12860 developed for HyperKamiokande [15]. Also shown parameters of the Super-Kamiokande Hamamatsu PMT R3600.

3.3 DUNE

The main scientific goals of the Deep Underground Neutrino Experiment (DUNE) [17] are the sensitive test of CP violation in the leptonic sector, determination the neutrino mass hierarchy, and precise measurements of neutrino oscillation parameters. The proposed far neutrino detector will be built deep underground, at a depth of about 1500 m, in the Sanford Underground Research Facility (South Dakota, U.S.A.), about 1300 km from Fermilab where a high intensity wide band on-axis neutrino beam with neutrino energies of 1–6 GeV will be formed. The near detector baseline design is a fine-grained tracker in a magnetic field, complemented by calorimetry and muon range detector. It will be located at a distance of 574 m from the target, at a depth of 65 m. The far detector will consist of four cryostats instrumented with Liquid Argon Time Projection Chambers (LAr TPCs) with a fiducial mass of 40 kt [18]. The LAr TPC technology offers excellent capabilities for position and energy resolution and for high-precision reconstruction of complex interaction topologies over a broad neutrino energy range and will provide a powerful complementarity to the large, underground water Cherenkov or scintillator-based detectors. It is expected that DUNE will reach a $3\sigma$ CP coverage of 75% and a $5\sigma$ coverage of 50% for an exposure of about 1 Mt×MW×year (20 years of running with the 40 kt detector and a 1.2 MW proton beam power). DUNE will determine neutrino mass hierarchy with a sensitivity $\geq 5\sigma$ for 100% of $\delta_{CP}$ values for 7 years of data taking (3.5 years in neutrino mode +3.5 years in antineutrino mode). These sensitivities still depend on the allowed range of values of other neutrino oscillation parameters. It is assumed that all four detector modules (figure 7) will be similar but not necessarily identical. According to the present timescale, DUNE begins data taking with the first 10 kton module in 2026 and the full configuration will be ready by 2029.

The first DUNE liquid argon module adopts a single-phase technology pioneered by ICARUS T600 detector. The single-phase TPC will be constructed by placing alternating high-voltage cathode planes and anode readout planes with a 3.6 m spacing in a bath of ultra-pure liquid argon. In this design, the charge is collected directly without gain, enabling precision charge calibration, but signal levels are low that motivates locating the front-end electronics in the LAr close to anode wires. This innovating approach requires the use of cold electronics. According to the reference design, the novel photon detection (PD) system will be comprised of inserted into anode plane assembly (APA) frame wavelength shifting bars with SiPM readout. A prototype of the single-phase TPC (700 t
Figure 7. DUNE far detector complex: 4 liquid Ar TPC modules with approximate dimensions 15(width) × 14(height) × 60(length) m³. Each module is able to contain a total mass of about 17000 t of liquid argon.

LAr TPC) will be constructed at CERN using 6 full size APAs with fully instrumented electronics and 6 cathode plane assemblies (CPAs). Its geometry is 6 m × 2.3 m cathode and anode planes with 3.6 m spacing as shown in figure 8(a). A reference PD module consists of a light guide and 12 silicon photo-multipliers (SiPMs), as shown in figure 8(b). The 128-nm photons from LAr interact with the wavelength shifter on the surface of the bar and the wavelength-shifted light, with a peak intensity around 430 nm, is re-emitted inside the bar and transported through the light-guide to SiPMs mounted at one end of the bar. The PD modules are mounted on the APA frames (figure 8(c)).
A few alternative photon detector designs which demonstrated the ability to detect the LAr light are currently being considered for the PD system. Data from the beam test of the single-phase TPC with PD system will provide input into the final technology decision.

In the dual-phase LAr TPC, the ionization electrons are vertically drifted (drift distance is about 12 m) in a constant electric field and extracted to a gaseous volume. Once extracted, electrons pass in the gas through a high electric field in the holes of a 1 mm thick LEM (Large Electron Amplifier) where they are amplified following avalanche cascades. The charge is collected on a two-dimensional and segmented anode. The expected signal-to-noise ratio is about $100:1$. The prompt scintillation light is detected with an array of cryogenic PMTs and used to provide the trigger signal and the absolute time reference for the charge readout electronics. The on-going LBNO-DEMO (WA105) experiment at the CERN Neutrino Platform [19] has to test all the principal components of the dual-phase technology necessary for building a multi-kt scale detector. In this experiment, two LAr dual-phase LEM TPC detectors, shown in figure 9, will be built and tested [20].

![Figure 9. The 20-t dual-phase prototype (a) and the $6 \times 6 \times 6 \text{ m}^3$ WA105 dual-phase demonstrator (b).](image)

The performance of a $3 \times 1 \times 1 \text{ m}^3$ pilot TPC detector with the total LAr mass of 24 t (figure 9(a)) will be measured with cosmics. A $6 \times 6 \times 6 \text{ m}^3$ (total LAr mass 700 t) demonstrator (figure 9(b)) will be exposed to particle beams at CERN. The second DUNE far detector module can be constructed on the basis of a dual-phase TPC if its performance is confirmed as a result of activities at the CERN Neutrino Platform.

The CERN Neutrino Platform provides the unique R&D and test facilities for DUNE detectors and components. The performance of a full scale single-phase TPC module will be characterized and a new technique for light detection in LAr will be learned. The functionality of cold TPC electronics will be verified. The technique of the dual-phase LAr TPC is expected to be proven. The goal of beam tests at CERN of the single- and dual-phase detector prototypes includes measurements of detector response to hadronic and electromagnetic showers, study of $e/\gamma$ separation, test of event reconstruction algorithms etc. The detectors are expected to start taking beam data at CERN in 2018.
4 Summary

Neutrino oscillations reveal physics beyond the Standard Model. Among many open neutrino questions, the discovery and study of leptonic CP violation, the determination of the neutrino mass hierarchy, and precision measurements of the oscillation parameters require novel massive neutrino detectors. Current long baseline accelerator experiments T2K and NOνA can obtain a $3\sigma$ sensitivity to CP violation and to the mass hierarchy, if parameters are favorable. T2K will benefit from the extended running time and the upgrade of the near detectors. The next generation long baseline experiments JUNO (scintillator detector), T2HK (Hyper-Kamiokande water Cherenkov detector), and DUNE (liquid argon TPCs) will have real chances to discover the mass hierarchy and CP violation with the sensitivity of $\geq 5\sigma$.

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References

[1] T2K collaboration, K. Abe et al., The T2K Experiment, *Nucl. Instrum. Meth. A* 659 (2011) 106 [arXiv:1106.1238].

[2] T2K collaboration, K. Abe et al., Measurements of neutrino oscillation in appearance and disappearance channels by the T2K experiment with $6.6 \times 10^{20}$ protons on target, *Phys. Rev. D* 91 (2015) 072010 [arXiv:1502.01550].

[3] T. Koga et al., Water/CH Neutrino Cross section Measurement at J-PARC (WAGASCI Experiment), *JPS Conf. Proc.* 8 (2015) 023003.

[4] M. Antonova et al., Baby MIND: A magnetised spectrometer for the WAGASCI experiment, arXiv:1704.08079.

[5] NOvA collaboration, P. Adamson et al., First measurement of electron neutrino appearance in NOvA, *Phys. Rev. Lett.* 116 (2016) 151806 [arXiv:1601.05022].

[6] DAYA BAY collaboration, F.P. An et al., Observation of electron-antineutrino disappearance at Daya Bay, *Phys. Rev. Lett.* 108 (2012) 171803 [arXiv:1203.1669].

[7] RENO collaboration, J.K. Ahn et al., Observation of Reactor Electron Antineutrino Disappearance in the RENO Experiment, *Phys. Rev. Lett.* 108 (2012) 191802 [arXiv:1204.0626].

[8] DOUBLE CHOOZ collaboration, Y. Abe et al., Indication of Reactor $\bar{\nu}_e$ Disappearance in the Double CHOOZ Experiment, *Phys. Rev. Lett.* 108 (2012) 131801 [arXiv:1112.6353].

[9] JUNO collaboration, F. An et al., Neutrino Physics with JUNO, *J. Phys.* G 43 (2016) 030401 [arXiv:1507.05613].

[10] Y. Heng, The Instrumentation of JUNO, talk presented at International Conference on Instrumentation for Colliding Beam Physics, Budker Institute of Nuclear Physics, Novosibirsk, Russia, 27 February – 3 March 2017.

[11] Q. Sen et al., Status of the large area MCP-PMT in China, *PoS(ICHEP2016)264.*
[12] Hyper-Kamiokande Proto-Collaboration collaboration, K. Abe et al., Physics potential of a long-baseline neutrino oscillation experiment using a J-PARC neutrino beam and Hyper-Kamiokande, *PTEP* **2015** (2015) 053C02 [arXiv:1502.05199].

[13] Hyper-Kamiokande Working Group collaboration, K. Abe et al., A Long Baseline Neutrino Oscillation Experiment Using J-PARC Neutrino Beam and Hyper-Kamiokande, arXiv:1412.4673.

[14] nuPRISM collaboration, S. Bhadra et al., Letter of Intent to Construct a nuPRISM Detector in the J-PARC Neutrino Beamline, arXiv:1412.3086.

[15] S. Nakayama, Recent Progress in the Development of Photomultiplier Tubes, PoS(PhotoDet2015)013.

[16] V. Berardi, The Hyper-Kamiokande detector: R&D studies of a new generation of Photosensors, talk presented at International Conference on Instrumentation for Colliding Beam Physics, Budker Institute of Nuclear Physics, Novosibirsk, Russia, 27 February – 3 March 2017.

[17] DUNE collaboration, R. Acciarri et al., Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE). Volume 2: The Physics Program for DUNE at LBNF, arXiv:1512.06148.

[18] DUNE collaboration, R. Acciarri et al., Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE). Volume 4 The DUNE Detectors at LBNF, arXiv:1601.02984.

[19] CERN Neutrino Platform, http://cenf.web.cern.ch/.

[20] W. Trzaska, WA105 experiment at CERN: large demonstrator of Dual Phase Liquid Argon TPC detector for DUNE, talk presented at International Conference on Instrumentation for Colliding Beam Physics, Budker Institute of Nuclear Physics, Novosibirsk, Russia, 27 February – 3 March 2017.

[21] L. Manenti, DUNE prototypes, talk presented at NuPhys2016: Prospects in Neutrino Physics, London, U.K., 12–14 December 2016.