Site selection for the new generation of giant neutrino detectors

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Abstract. The main findings of the LAGUNA Design Study are briefly discussed. Construction of giant underground detectors is technically feasible at several sites. Physics factors will dominate in the site selection.

1. Introduction

Super-Kamiokande [1] and its predecessor Kamiokande [2] are among the most successful experiments of modern physics. They have provided crucial measurements of solar, atmospheric, Supernova and beam neutrinos and recently the first indication for the non-zero value of the neutrino mixing angle \(\theta_{13}\) [3]. This success was possible thanks to the large mass of the detector, multitude of photosensors, and a thick overburden providing adequate shielding from the background induced by cosmic rays. The Super-K tank holding 50 kton of ultra pure water and incorporating 13 000 PMTs is located 1 km underground in the Kamioka mine in Japan. To improve on that impressive achievement one needs a detector that would bring an improvement in the sensitivity of at least one order of magnitude. This in turn could be reached either by increasing the size or through the improved detection techniques. LAGUNA – Large Apparatus studying Grand Unification and Neutrino Astrophysics – is the European response to the quest to reach and cross the next discovery threshold.

Building of a giant neutrino detector requires a cavern with a span of up to 100 m. The desired thickness of the overburden reaches up to 1.4 km of solid rock. These extreme requirements are clearly at the limits of the present technology. The recently completed LAGUNA Infrastructure Design Study has investigated the feasibility and estimated the possible costs of such excavations. This paper summarizes the main findings that will be available in full detail in the deliverables given to the European Commission.

2. Detectors and Requirements

The three detector technologies considered by LAGUNA are called GLACIER (liquid argon), LENA (liquid scintillator) and MEMPHYS (water Cherenkov). The water Cherenkov option [4] is modeled after Super K but envisions an order of magnitude increase in size to reach 500 kton of the fiducial mass. To contain such gigantic volumes, at least two water tanks must be constructed, each holding a total of 330 kton of water. Therefore, each tank and each cavern will be about 6 times larger than Super-K. Although the water Cherenkov detector technology is well understood, the engineering challenge connected with the construction is considerable and the
requirements for the rock quality very high. The minimum desired overburden for MEMPHYS is 3000 m.w.e. (1100 m of rock). The strongest advantages of MEMPHYS are the well-proven, robust technology, lowest cost per mass unit, and the largest proposed fiducial mass.

Thanks to the many virtues of liquid scintillators such as good energy resolution, high light output, low detection threshold, excellent background discrimination, etc. LENA [5] will bring a significant improvement in performance over Super-K without the need to grow the size beyond the 50 kton mark set by the Japanese detector. Just like in the case of water Cherenkov, the technology to produce a scintillator detector is well understood. However, since the largest scintillator detectors build so far [6] are only in the range of 1 kton, up scaling by a factor of 50 will not be a trivial exercise. Also the cavern will have to be twice as tall as Super-K’s as the scintillator has lower transparency. Lower transparency requires reduction of the diameter of the tank. To reach the same mass, the cylindrical tank must be taller. To fulfill its rich physics program LENA must be very well shielded from the cosmic muons. The minimum required overburden is 4000 m.w.e. (1400 m of rock). The main advantages of LENA are the lowest energy threshold, proven technology and the lowest total cost.

GLACIER [7] proposes by far the most advanced detection technology of all LAGUNA detectors offering impressive tracking abilities and sophisticated background rejection. With the target mass of 100 kton of liquid argon it would be the best far detector ever build for neutrino oscillation studies and an excellent tool for astroparticle physics and the search for proton decay. Unlike MEMPHYS and LENA it can be located at a moderate depth as the required overburden is 2500 m.w.e. (900 m of rock). The biggest challenge for GLACIER is the detector technology. The largest operating LAr detector is ICARUS T600 [8] with only 480 ton contained in the sensitive volume.

3. Outcome of LAGUNA Design Study
LAGUNA Design Study was supported over the period 2008 – 2011 with 1.7 MEUR by the FP7 Research Infrastructure "Design Studies" LAGUNA (Grant Agreement No. 212343 FP7-INFRA-2007-1). Seven potential European sites were evaluated: Pyhäsalmi in Finland (mine), Frjus in France (road tunnel), Boulby in the UK (mine), Umbria region in Italy (virgin site), Sieroszowice in Poland (mine), Canfranc in Spain (road tunnel) and Slanic in Romania (mine). In each site up to three detector options were studied. The work involved over 100 physicists and engineers from 10 countries. The main outcome of the Design Study is that the giant caverns required by LAGUNA detectors are technically feasible and cost effective. The price tag for excavation and preparation of the underground space is only in the range of 10–20% of the total costs. All of the investigated sites have geological strata suitable for the construction of large caverns and high level of engineering competence to build and maintain such structures. While the rock with the best parameters was found in Finland, no other site was excluded for the lack of geological formations suitable for the construction, as there are adequate technical means to compensate for rock imperfections. Since all seven European sites are technologically suitable to host LAGUNA, physics arguments should provide the deciding factors for the final site selection.

4. Physics Factors
If the new giant detector is to serve as the far detector for neutrino oscillation studies, the length of the baseline becomes the key parameter in the choice of the site. CERN is currently the only European provider of neutrino beams [9] making the distance from CERN and the possibility to construct the beam line and the near detector along the line pointing towards the potential site the most important physics criterion for the location of the neutrino observatory. These topics are the focus of LAGUNA LBNO (Long Baseline Neutrino Oscillations). LAGUNA LBNO started on September 1st 2011 and will last for three years. It is the second and the final Design Study for LAGUNA supported in part by the FP7 Research Infrastructure Grant.
By the time LAGUNA becomes operational, the missing mixing angle $\theta_{13}$ will most likely be already known through experiments like T2K, Minos, Double Chooz, and others. Therefore, the main goal of the oscillation studies with LAGUNA would be the determination of the mass hierarchy and of the CP violation phase. According to the calculations based on the known values of the oscillation parameters and taking into account technical limitations, the ideal baseline for such studies is around the bimagic value of 2540 km. At that length and for the selected neutrino energy there is a very clear difference in the oscillation probability (appearance of the specific neutrino flavor) between the inverted and non-inverted scenario that is nearly independent from the other unknown parameters such as the phase of CP violation (see Fig. 1).

Figure 1. At the baseline of 2300 km (CERN – Pyhäsalmi) there is a very clear separation between the oscillation probabilities for inverted and non-inverted hierarchy for all phases of the CP mixing angle.

In other words, at the baseline close to the bimagic value a relatively small detector should be sufficient to provide a decisive result, for instance, on the mass hierarchy. That would not be possible with the same detector placed at half the distance since the separation would be much less pronounced requiring in turn higher statistics (longer exposure and larger fiducial volume). Paradoxically, the neutrino flux is comparable in both cases because at larger distances the relevant oscillation maxima/minima appear at higher neutrino energies. By increasing the energy of the primary beams the neutrinos originating from the decay of the secondary particles produced in the reactions experience a kinematic boost providing forward focusing that compensates for the longer baseline.

There are two more parameters that have an impact on the performance of a giant neutrino detector: overburden, and neutrino background. Figure 2 summarizes the overburden requirements for the three detector types and the maximum depth provided by each of the proposed LAGUNA sites.

For the study of low energy neutrinos that are possible only with the liquid scintillator, one must also consider the background generated by the numerous power reactors. Fig. 3 was calculated [10] from the database of all European nuclear power plants including those scheduled to open within 5 years. For simplicity and to avoid periodic fluctuations caused by the duty cycle of reactor, the calculations show all the stations operating at the nominal power.
Figure 2. Overburden in m.w.e. at all proposed LAGUNA sites compared to detector requirements.

Figure 3. Background level in TNU induced by power reactors.

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