LAGUNA IN PYHÄSALMI*

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(Received April 20, 2010)

Pyhäsalmi mine in Finland is evaluated as one of the seven proposed sites to host LAGUNA — Large Apparatus studying Grand Unification and Neutrino Astrophysics. A number of arguments based on geology, background from nuclear power plants, political and legal conditions, as well as engineering analysis and the presence of the needed infrastructure are all in favour of the Finnish site.

PACS numbers: 95.45.+i

1. Introduction

The main physics requirement for the site to host a LAGUNA-type detector [1] is to guarantee that the desired background conditions are fulfilled. The main source of the background is the flux of energetic muons induced by cosmic-rays hitting the upper layers of the Earth atmosphere. Although muons could easily be rejected by a veto detector, this approach increases

* Presented at the Cracow Epiphany Conference on Physics in Underground Laboratories and Its Connection with LHC, Cracow, Poland, January 5–8, 2010.

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the dead time of the detector. Therefore, a large and sensitive detector must be located deep underground to operate efficiently. The minimum overburden required for the three detector types proposed within LAGUNA are estimated to be: GLACIER 2500 meters of water equivalent (corresponding to 900 metres of hard rock), MEMPHYS 3000 m.w.e. (1100 m of rock) and LENA 4000 m.w.e. (1400 m of rock) [2].

The second physics requirement is the distance from CERN to the detector site. This parameter is relevant when CERN starts the construction of high-energy and intensity neutrino beams. At 2300 km, Pyhäsalmi provides optimal location for neutrino oscillation experiments if the planned neutrino factory will be realized. Concerning LENA there is also the third requirement — to minimize neutrino background generated by nuclear power reactors.

While physics requires going deep underground, the geological, engineering, logistic and economic arguments all favour accommodating the detector at the minimum acceptable depth. In the end, the best location is the one where the required cavern could be build at the required depth for the lowest cost, in the shortest time, and with the minimal negative impact on the environment. In this paper we present arguments pointing to the conclusion that the Pyhäsalmi mine fulfills all these conditions and provides the best location for all three detector designs proposed by LAGUNA. Figure 1 shows the proposed outline to place all three LAGUNA detectors in the Pyhäsalmi mine.

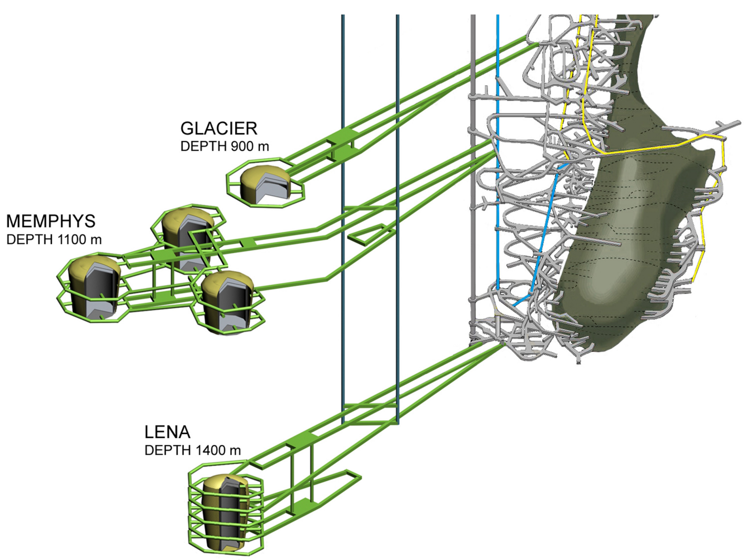

Fig. 1. All three LAGUNA detectors located in Pyhäsalmi.

TABLE I

Distances from Pyhäsalmi to the relevant destinations.

Destination	Distance (km)
Nearest landing strip	8
Nearest fully equipped hospital	69
Oulu city centre	164
Oulu international airport	167
Jyväskylä city centre	183
Jyväskylä international airport	163
Kokkola (sea port)	163
Helsinki city centre	449
Helsinki airport	439

2. General information

The Pyhäsalmi mine (63°39′31″ N–26°02′48″ E) is located within the Pyhäjärvi municipality of 6000 inhabitants, close to the geographical centre of Finland, on the crossing of highway 4 (E75) — the main North–South road — with highway 27 — an important East–West route. Along that route there is also a railway stop in the town and a junction to the railroad yard in the mine. Pyhäsalmi has a clinic serving the local population, schools, kindergartens and a local airfield. There are several restaurants, a 33-room hotel, a year-round camping with heated cottages, and several B&B places. The nearest large towns are Oulu (140 000 inhabitants) and Jyväskylä (130 000 inhabitants). Oulu — the regional capital — has a large, multidisciplinary University (16 000 students) including the Faculty of Science and the Faculty of Technology. There are frequent daily flights to Oulu as it is the second busiest airport in Finland. One can also fly to Jyväskylä — the town renown for its educational character with 40 000 students and pupils of which 16 000 are at the University of Jyväskylä.

Pyhäsalmi Mine Ltd is owned by the Canadian company Inmet Mining Corporation. The mine produces copper, zinc and pyrite. The exploitation depth between 1100 and 1400 metres means it is the deepest mine in Europe. At the current market prices, the known ore resources will keep the mine in operation until 2018. The mine has an excellent efficiency and safety record. It employs directly 220 people and through the sub-contractors, 50 more. The mining is done only on weekdays during the morning and evening shifts. Blasting is done at 10 o'clock in the evening. Normally, after the explosions, there is no access to the mine before 6 o'clock the next morning.

3. Geology and background conditions

Finnish bedrock is among the oldest (3.5–2.6 Ga) and hardest in Europe. It is tectonically stable. Thanks to the experience collected during the five decades of mining activities in Pyhäsalmi, the local geological conditions are very well known. The access tunnel has been excavated half-a-way to within 250 m from the deepest proposed cavern — the one for LENA detector — and drilling samples were taken from the area. The major principal stress is horizontal bearing to NW (310°). The rock has been classified as Mafic and Felsic Volcanites with elastic behaviour and a risk of spalling. The peak rock strength is 232 MPa, the Geological Strength Index is 77, and the Rock mass strength $\sigma_{\rm cm} = 132$ MPa [3].

The average air temperature at the surface varies from −9°C (in January) to +16°C (in July). The measured temperature at the depth of 90 metres is +9°C and does not change significantly with the seasons. The temperature gradient is nearly linear reaching +16°C at 900 m and +22°C at 1400 metres. Below 700 metres the rock conditions are dry and the rock is very solid. The radon content in the ventilated underground areas is regularly monitored and remains at the level of 20 Bq/m^3.

TABLE II

In situ stress before excavation at the depth 900–2000 m.

Depth (m)	σ_{H1} (MPa)	σ_{h2} (MPa)	σ_v (MPa)
900	52	33	26
1100	64	40	32
1400	81	51	41
2000	116	73	58

3.1. Reactor neutrinos

The physics program for LENA (Low Energy Neutrino Astrophysics) includes studies of diffuse supernova and geoneutrinos with energies overlapping with neutrino spectra from the fission of reactor fuel (Fig. 2). A high level of reactor neutrinos, for instance in the proximity of a nuclear power plant, would significantly reduce the sensitivity of LENA to neutrinos with energy below 8 MeV. Therefore for LENA, a location with the lowest level of reactor neutrinos is strongly favoured. Table III lists the calculated neutrino fluxes for each of the proposed LAGUNA sites. In the calculation we have accounted for all the commercial nuclear power plants operating in 2009 (Fig. 3). Using the precise location of each plant and assuming that all the reactors run at the maximum thermal power, the total flux of neutrinos for each site was calculated and is listed in the second column of Table III.

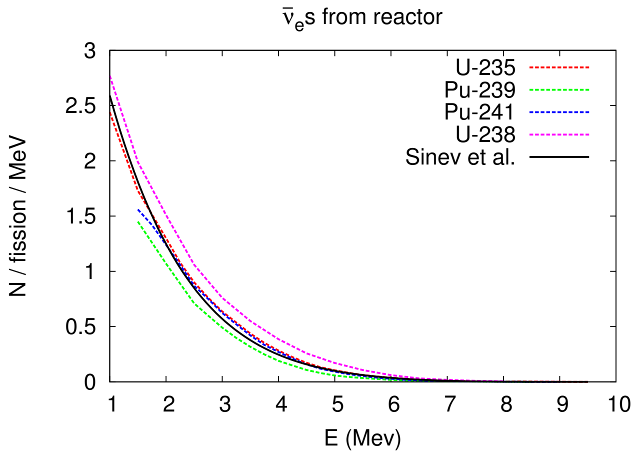

Fig. 2. Energy spectrum of electron anti neutrinos emitted during beta decay chains following fission of reactor fuel.

Due to oscillations, only part of the emitted neutrinos arrives as electron antineutrinos, as listed in the third column. To make the results easier to apply, they are also given as the expected annual rates in 1 kiloton of liquid scintillator (containing 10^{32} of free protons).

TABLE III

Calculated neutrino fluxes from the known nuclear power reactors. The last column contains the expected event rate in one kiloton of scintillator (containing 10^{32} of protons).

Location	$\Phi_{\max}$ $[10^9\ \mathrm{m}^{-2}\mathrm{s}^{-1}]$	$\Phi_{\bar{\nu}_e}$ $[10^9\mathrm{m}^{-2}\mathrm{s}^{-1}]$	Events $[\mathrm{kton}^{-1}\mathrm{a}^{-1}]$
Pyhäsalmi (FIN)	1.44	0.74	73
Caso (ITA)	2.10	1.07	106
Slanic (ROM)	2.41	1.25	122
Sieroszowice (POL)	3.63	1.86	182
Canfranc (ESP)	5.42	2.80	275
Frejus (FRA)	11.90	6.21	645
Boulby (GBR)	25.10	10.50	1470

Fig. 3. Location of the 7 proposed LAGUNA sites and of all known nuclear power stations operational in 2009 (circles).

4. Political and legal status

Finland is a full member of European Union since 1995, is the home base of several international high-tech companies, has the highest percentage of GNP devoted for science and education, and is the leader in many school evaluation surveys. Nevertheless, until now, no high-profile EU project, institute, or commission has been allocated to Finland. This imbalance creates a very receptive attitude of the Finnish political elite towards large European projects like LAGUNA. Based on our preliminary interviews with the top politicians and the relevant ministries, the government of Finland would be willing to participate in LAGUNA construction costs if Pyhäsalmi were chosen as the host. There is also a very enthusiastic support for this project by the town and district administration as well as the local population. In fact it was through the local initiative that the Centre for Underground Physics in Pyhäsalmi (CUPP) was established ten years ago.

4.1. Cosmic-ray experiment EMMA

Currently, the main activity at CUPP is the cosmic-ray experiment EMMA (Experiment with MultiMuon Array) [4]. The main aim of EMMA is to resolve the cosmic-ray composition in the knee region by measuring the lateral distribution of high energy muons. Three of the planned nine measuring stations are now completed at a depth of 75 m ($\sim$ 210 m.w.e.), corresponding to 45 GeV muon cut-off energy. The tracking accuracy is $\sim$ 0.5 degrees. Figure 4 shows a reconstructed 32-muon event detected by an underground tracking unit. The unit consists of three layers of position sensitive detectors. Each layer is made of 5 detector planks (former LEP-DELPHI MUBs). There are seven individual drift chambers per plank [5]. By the end of 2010 a fourth detector layer will be installed. It will consist of an array of scintillators, 3 cm thick $12 \times 12\,\text{cm}^2$ each [6] This fourth layer is needed to study high-density multi-muon bundles that would otherwise saturate the drift chambers.

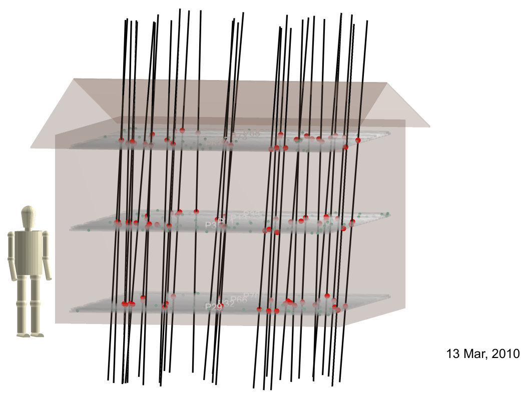

Fig. 4. Reconstruction of a multi-muon event recorded by one 3-layer EMMA detector station.

4.2. Collaboration with the mine

During the decade of the presence of CUPP in the mine and especially since the start of the construction and operation of EMMA, very good work atmosphere and arrangements have been developed between the mine and the scientific community. In 2009 this cooperation received a legal status through the signing of Memorandum of Understanding. The signatories were the mine management, Rectors of Oulu and Jyväskylä Universities and Rockplan Ltd — the technical partner involved in research and develepement for LAGUNA. A preliminary location was chosen for LAGUNA.

The detectors, support structures and ground facilities would all be situated on the territory of the mine. This is a major advantage as the mine already has the excavation and construction permits and the related environmental issues have already been resolved.

5. Engineering evaluation

The hard and very old bedrock in Finland provides excellent environment to support the giant deep-underground caverns needed for LAGUNA detectors. The rock has a suitable low temperature and is tectonically stable. Finland has developed high expertise in the design and construction of large, complex underground excavations and constructions as good rock conditions are present not only in Pyhäsalmi but all over the country. Nevertheless, the presence in the mine of a ready access tunel (decline) spiralling all the way down to -1410 m level, of an efficient transport hoist shaft, and of a ventilation shaft reduces considerably the cost and the construction time. Further, the mine has an excellent rail yard with good connections, also by road, to the harbour in Kokkola and other seaports. There is ample storage area on the surface. The decline allows for the construction of the dedicated LAGUNA tunnels directly at the desired depth. All the excavated rock (up to the capacity of 250 000 m^3/year) can be used by the mine without the need to bring it to the surface reducing the construction cost. Finally, the mine has very suitable hydrological conditions. The deep rock is dry and does not exhibit any time related deformations like the creep present in salt or anhydrite layers.

6. Conclusions

Pyhäsalmi mine is in the unique position among the proposed LAGUNA sites. It has the best rock and background conditions, ready infrastructure, clear legal status, and strong support both from the local and from the central government. The construction could technically start any moment now and would be completed in the shortest time (see Table IV).

TABLE IV

The estimated time and cost for the construction of the underground infrastructure for the three LAGUNA detectors.

Detector	Construction time (a)	Estimated cost (MEuro)
GLACIER	3	45
MEMPHYS	7	130
LENA	4	75

Even the horizontal access tunnel has already been excavated to within 250 m from the proposed location of LENA — the deepest of the detectors. In Pyhäsalmi all three detector types could be accommodated simultaneously making it truly the ideal site for LAGUNA.

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