CERN-ACC-2013-0271

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Report

Design Study for a Future Laguna-LBNO Long-Baseline Neutrino Facility at CERN

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Keywords: Hadron Accelerators, High Intensity Accelerators

Abstract

The Large Apparatus studying Grand Unification and Neutrino Astrophysics (LAGUNA) study [1] investigated seven pre-selected underground sites in Europe (Finland, France, Italy, Poland, Romania, Spain and UK), capable of housing large volume detectors for terrestrial, accelerator generated and astrophysical neutrino research. The study was focused on geo-technical assessment of the sites, concluding that no show-stoppers exist for the construction of the required large underground caverns in the chosen sites.

The LAGUNA-LBNO FP7/EC-funded design study extends the LAGUNA study in two key aspects: the detailed engineering of detector construction and operation, and the study of a long-baseline neutrino beam from CERN, and possibly other accelerator centres in Europe. Based on the findings of the LAGUNA study, the Pyh¨asalmi mine in Finland is chosen as prime site for the far detector location.

The mine offers the deepest underground location in Europe (-1400 m) and a baseline of 2’300 km from CERN (Fig. 1). Two large caverns for LArgon (2 × 50 kt) and magnetised detectors are foreseen, and a third large cavern housing a 50 kt Liquid Scintillator detector is also planned.

Presented at: IPAC13, 12-17 May 2013, Shanghai, China

Geneva, Switzerland
June, 2013

DESIGN STUDY FOR A FUTURE LAGUNA-LBNO LONG-BASELINE NEUTRINO FACILITY AT CERN*

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Abstract

A design study for a Long Baseline Neutrino Oscillation experiment (LBNO) with a new conventional neutrino beamline facility at CERN was initiated in September 2011, supported by EC/FP7 funds. The beam will serve a next generation deep-underground neutrino observatory located at the Pyhäsalmi (Finland) mine at a distance of 2300 km from CERN. The paper will focus on the design challenges of this MegaWatt-class facility and on the optimisation studies of the secondary beam elements to produce a neutrino beam spectrum for the proposed neutrino oscillation physics programme aimed in particular at the neutrino mass hierarchy determination and CP-violation discovery in the leptonic sector.

INTRODUCTION

The Large Apparatus studying Grand Unification and Neutrino Astrophysics (LAGUNA) study [1] investigated seven pre-selected underground sites in Europe (Finland, France, Italy, Poland, Romania, Spain and UK), capable of housing large volume detectors for terrestrial, accelerator generated and astrophysical neutrino research. The study was focused on geo-technical assessment of the sites, concluding that no show-stoppers exist for the construction of the required large underground caverns in the chosen sites. The LAGUNA-LBNO FP7/EC-funded design study extends the LAGUNA study in two key aspects: the detailed engineering of detector construction and operation, and the study of a long-baseline neutrino beam from CERN, and possibly other accelerator centres in Europe. Based on the findings of the LAGUNA study, the Pyhäsalmi mine in Finland is chosen as prime site for the far detector location. The mine offers the deepest underground location in Europe (-1400 m) and a baseline of 2'300 km from CERN (Fig. 1). Two large caverns for LArgon (2 × 50 kt) and magnetised detectors are foreseen, and a third large cavern housing a 50 kt Liquid Scintillator detector is also planned.

THE CN2PY BEAM

The long-baseline CERN Neutrinos to Pyhäsalmi (CN2PY) beam is a conventional third generation neutrino beam facility based on the CNGS [2] technology. The scientific program of LBNO [3] extends in two phases. Initially, the facility will use an upgraded beam from SPS reaching 750 kW of nominal beam power.

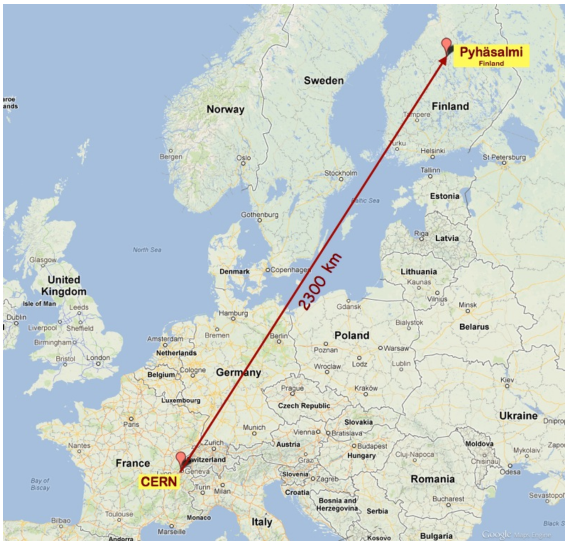

Figure 1: Schematic view of the CERN to Pyhäsalmi neutrino beam (CN2PY).

This high-intensity operation goes beyond the record intensity of 565 kW ever achieved in the SPS [4], and 60% above the operational beam power for CNGS. The main limitations to achieve such intensities come from beam losses in both PS and SPS, and due to limited RF power at SPS. In Table 1 the expectations for the SPS potential in delivering intense beams for a future neutrino program

Table 1: Present, All-time Record, and Possible Future SPS Parameters for Neutrino Type Beams

	CNGS	RECORD	CN2PY
E_{SPS} [GeV]	400	400	400
Bunch spacing [ns]	5	5	5
I_{bunch} [$\times 10^{10}$]	1.05	1.3	1.7
$N_{bunches}$	4200	4200	4200
I_{SPS} [$\times 10^{13}$]	4.4	5.3	7.0
I_{PS} [$\times 10^{13}$]	2.3	3.0	4.0
PS cycle length [s]	1.2	1.2	1.2/2.4
SPS cycle length [s]	6.0	6.0	6.0/7.2
E_{PS} [GeV/c]	14	14	14
Beam power [kW]	470	565	747/622

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* Work supported by EC/FP7 grant 284518

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are described, coming as stretched goal within the foreseen LHC injector upgrades (LIU) project [5]. Detailed studies of the full performance potential are on-going, and will be reported at the end of the design study in September 2014.

For the second stage, the proton beam to CN2PY will be upgraded with the construction of a new high-power proton synchrotron (HP-PS) designed to deliver a beam in the range of $50 \div 75$ GeV at 2 MW of beam power [6]. Table 2 summarises the key parameters for the beam. The quoted yearly intensities correspond to 200 days of running with 80% efficiency for the accelerators, and $60 \div 85$% of beam sharing with other users for the case of SPS.

Table 2: Key Parameters of the CN2PY Beam for the SPS and HP-PS Phases

Parameter	SPS beam	HP-PS beam
$E_{\text{beam}}[GeV]$	400	$50 \div 75$
$I_{\text{beam}}[ppp]$	7×10^{13}	$2.5 \div 1.7 \times 10^{14}$
Cycle length [s]	6	1
$P_{\text{beam}}[MW]$	0.750	2
$\text{POT}_{\text{year}}\ [10^{21}]$	$0.10 \div 0.14$	$3.46 \div 2.35$

To profit from existing infrastructure for the target hall and near detector, in the baseline option, the CN2PY beam is located near the SPS Noth Area as shown in Fig. 2.

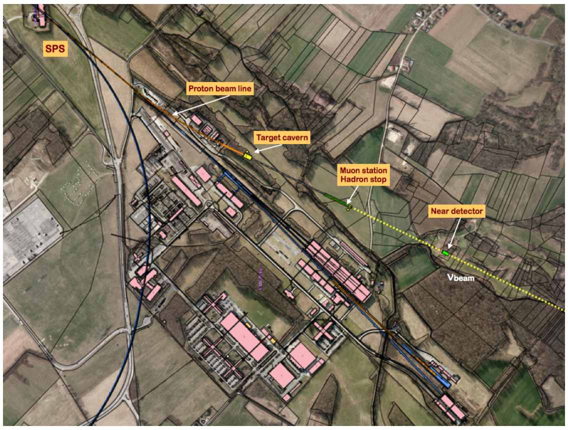

Figure 2: The baseline layout for the CN2PY neutrino facility in the vicinity of the SPS North Area.

For the first stage using the 400 GeV from SPS, the primary beam is extracted from the TT2 channel and transported for about 400 m in the existing TT20 line. Then it branches off to a new 480 m long transfer line required to match the direction and more importantly create the 10.4 deg downwards slope required to point to the far detector.

For the fast extraction from SPS in the Long Straight Section-2 (LSS2), a novel scheme was developed to bypass the lack of space to install new kickers in the region whilst maintaining the elements required for the slow extraction to fixed-target experiments. The new scheme, uses a non local extraction combining kickers in LSS6 and LSS2 sections. First tests with beam show encouraging results, further studies are planned after the restart of the CERN accelerators in 2015 [7].

A key constraint in the location and design of the CN2PY secondary beam comes from the steep 18.1% slope required due to the long-baseline. The combination of high-intensity and high beam energy of 400 GeV for the initial operation, in the baseline assumption requires the near detector to be, assuming a rock density of 2.3 g/cm^3, at 800 m distance from the target in order for the high-energy muons to be absorbed in the earth in between. As a consequence, the near detector cavern will be 144 m deeper from the target. Therefore the option to branch off from the TT20 line at its upmost point very close to the surface is very attractive, as it allows the whole installation to be at smaller depth with significant cost savings. In this configuration the target cavern is located at -41 m, the hadron stop at -100 m and the near detector at -185 m, almost at the same level as the deepest point of LHC.

The layout of the CN2PY facility when using the proton beam from HP-PS is shown in Fig. 3. A new transfer line transversing SPS at higher depths will transport the extracted proton beam from HP-PS until it joins the new line out of TT20, upstream the neutrino target. The detailed evaluation of the baseline layout of the facility is ongoing, in parallel to alternative variants interesting for technical, operational or cost saving reasons (see also [8]).

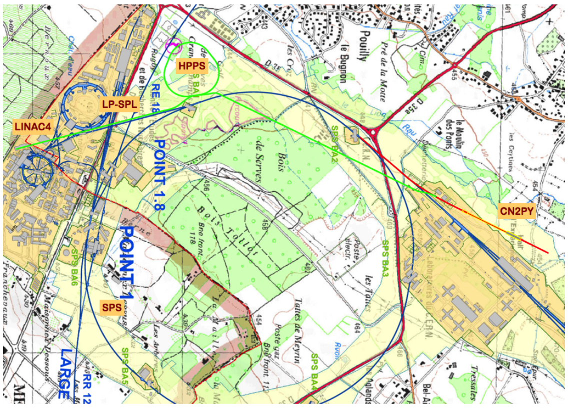

Figure 3: The CN2PY beam layout in the second phase using the proton beam from HP-PS.

THE NEUTRINO BEAM

CN2PY will be a new (third) generation conventional neutrino beam based on the CNGS technology and experience at CERN. The neutrino beam (ν_μ) is produced from meson (pion/kaon) decays in a 300 m long 1.5 m radius decay volume downstream the two magnetic focusing elements (horns) downstream the production target (Fig. 4).

The secondary beam infrastructure will be the same for all phases, designed from the beginning for the 2 MW operation. The design will be flexible to allow a different rel-

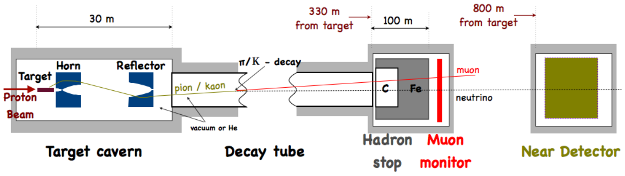

Figure 4: Schematic view of the CN2PY secondary neutrino beam. The elements are not to scale.

ative configuration of the target and focusing elements that must be optimised separately for the two energy regimes. The hadron stop will be followed by a long muon shielding required to reduce the muon rate to the near detector below the presently assumed limit of 2.5 μ/m^2 per 10^{13} pot (Fig. 5).

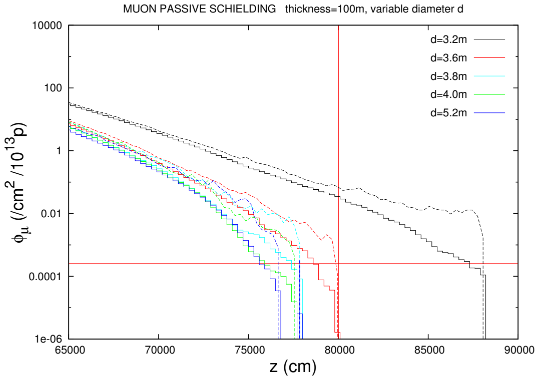

Figure 5: Muon fluxes downstream the hadron stop for various diameters of a 100 m long iron shielding. The full lines correspond to the total flux over a 5×5 m^2 area, whereas the dashed lines to the maximum value in the same area. The horizontal line is the acceptable muon rate limit, and the vertical line the foreseen location for the near detector.

Optimisation studies for the design of the secondary beam are performed using the FLUKA simulation package and full tracking of the secondaries. In the present configuration, the target is a solid 1.3 m long graphite ($\rho = 1.75$ g/cm^3) rod of 4 mm radius, located like CNGS just outside the horn. The horn and reflector have an inner conductor of parabolic shape optimised mainly to focus the low-energy secondaries corresponding to the first oscillation maximum ($E_\nu = 3 - 6$ GeV), whereas the neutrino flux at the second oscillation maximum ($E_\nu = 1 - 2$ GeV) is limited by the geometrical acceptance of the focusing system. The expected neutrino fluxes for the four different neutrino species at the near and far on-axis detectors in this configuration are shown in Fig. 6.

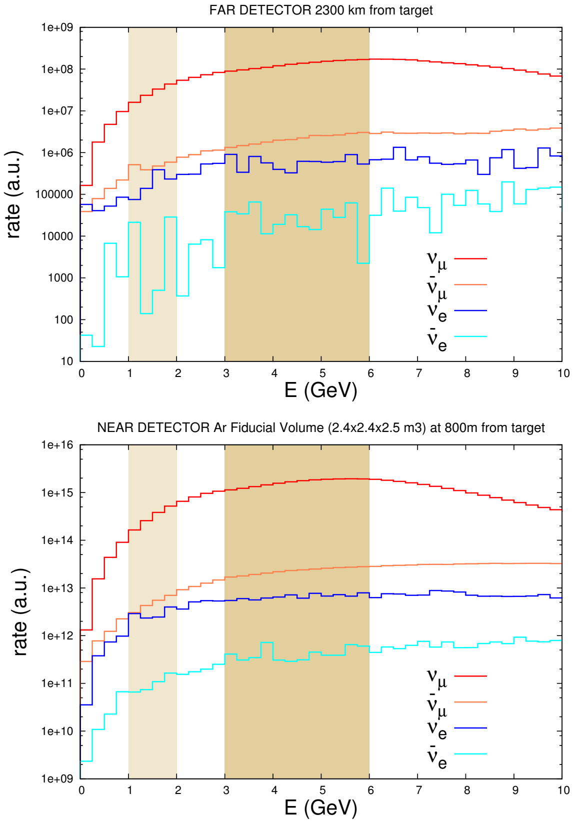

Figure 6: Expected neutrino spectra at the far (top) and near (bottom) detector. The shaded regions correspond to energy bands around the first ($E_\nu = 3 - 6$ GeV) and second ($E_\nu = 1 - 2$ GeV) peak of the ν_μ oscillation probability where the sensitivity to the oscillation parameters is maximal.

CONCLUSION

The beam options for the LAGUNA-LBNO design study include a new 2'300 km long-baseline neutrino beam at CERN, developed in two phases:. an initial 750 kW operation using the 400 GeV beam from SPS, to 2 MW operation using a $50 \div 75$ GeV beam from a new high-power PS. The baseline layout for the facility integrated in the CERN complex was presented. The steep 18%, slope of the beam due to the long-baseline introduces interesting engineering challenges to the design of the facility. A first design of the target and focusing system of the neutrino beam is made, further optimisation studies will be performed with the goal to enhance the neutrino rate at the far detector for the second (low-energy) oscillation peak that is most relevant for the CP-violation search.

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