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PERFORMANCE ANALYSIS AND PHYSICS POTENTIAL OF UPGRADES OF EXISTING NEUTRINO FACILITIES

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PERFORMANCE ANALYSIS AND PHYSICS POTENTIAL OF UPGRADES OF EXISTING NEUTRINO FACILITIES

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Abstract

The performance of the CERN Neutrino to Gran Sasso (CNGS) facility and its upgrade potential has been reviewed. Mid-term options such as the creation of new conventional neutrino beams from the CERN Super Proton Synchrotron (SPS) that built upon the CNGS technology have been explored. Longer-term prospects of these, involving further upgrades of the CERN accelerator complex, as well as other concepts such as a neutrino factory, a beta-beam or a multi-MW neutrino super-beam studied within the EC-funded FP7 EUROnu activity mapped to the CERN infrastructure are presented. Highlights of the required R&D effort and technical challenges are discussed.

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Contents

1 Introduction

Neutrinos are among the fundamental particles in the Standard Model (SM), and nowadays probably the most intriguing part of it! They are included as massless spin ½ particles, and for several decades the search of their properties have been the subject of many experiments worldwide. The discovery at the end of the last century that neutrinos that come from the Sun or generated in the Earth's atmosphere change flavour as they propagate in space – baptized as neutrino oscillations, imply that neutrinos contrary to the SM prediction have mass and there is a flavor-mixing mechanism described by a complex 3×3 matrix.

Experiments that followed this discovery measured the neutrino mixing angles θ_{12}, θ_{23}, and recently θ_{13}, all found to be non-zero and large. The full understanding of the complex neutrino-mixing matrix, and in general the underlying theory of neutrinos is one of the key quests in the particle physics today. Neutrinos, via a possible Charge-Parity (CP)-violation, may have played an important role in the early phases of the Universe in the baryon asymmetry and matter to anti-matter dominance that we observe today.

The present generation of experiments in accelerator-based neutrino oscillation facilities: CNGS [1] in Europe, NuMI [2] in the United States and T2K [3] in Japan, was designed to confirm the neutrino oscillations using man-made neutrinos, and measure the mixing angles, θ_{13} in particular. With that goal achieved, upgrades of the existing installations to high-power (thus more ν-flux) coupled to a new generation and larger mass of neutrino detectors are studied. And in a further step, new high-power and high-precision neutrino sources (better neutrino beam quality and less systematic uncertainties in ν-flavor content) are planned. The goal of these new experiments is to provide answers on the neutrino Mass Hierarchy (MH), the presence (or not) and study of leptonic Charge-Parity (CP) violation and further, precision studies of the neutrino mixing parameters.

CERN is presently operating the CERN Neutrino to Gran Sasso (CNGS) beam, which in December 2012 completed its approved physics program. The design and operation of this second-generation conventional neutrino beam facility provides important expertise towards the realization of future projects. CNGS uses a proton beam from the Super Proton Synchrotron (SPS), which today offers sufficient beam power at the sub- MW range to create competitive neutrino beams for neutrino oscillation physics. EC-funded design studies, where CERN participates, investigate upgrade options or future beams based on the gained experience from CNGS. The new ν-beam faciliteis and the new generation of experiments, would help to reconstitute the European neutrino physics community and enhance the collaborations between European and non-European institutes, gathering experts worldwide.

Building on the foreseen LHC Injectors Upgrade (LIU) [4], the conventional neutrino beam technology of CNGS could remain competitive for long baseline facilities, once optimized to produce the softer, few GeV, neutrino beams favoured by the recent measurement of θ_{13}. Such a beam, successor to CNGS, has been proposed under the LAGUNA-LBNO [5] collaboration to a long-baseline (2'300 km) detector site located in the Pyhasalmi mine in Finland, for unique physics opportunities, complementary to the international neutrino physics present and foreseen program. In the longer term, depending on the physics landscape at that time, the long baseline facility could be upgraded to reach additional physics goals such as precision measurements in the leptonic sector, using either the conventional beam with an upgraded high-power (2 MW) proton driver, or a low-energy (10 Gev muons) Neutrino Factory also well adapted to the same long-baseline. Alternatively for this second phase, new type of detectors in a medium (130 km) baseline site using the few hundred MeV neutrinos from a high-power (4 MW) super-beam and/or a 1 MW, $\gamma = 100$ β-Beam can be envisaged.

It is more than evident that such large-scale programs require global coordination and large investments to be realized. The staged approach for CERN based neutrino beams as outlined above has been submitted [6], along with other options like the one studied in EUROnu FP7/EC design study [7] to the European Strategy Process as input to the Crakow Meeting [8]. As starting stage for this new generation of beams, the concept of a Neutrino Test Facility in the SPS North Area has been proposed [9] and is currently under consideration, with a twofold goal: a) provide a short baseline conventional neutrino beam in support of sterile neutrinos search as proposed by the ICARUS [10] and NESSIE [11] collaborations and b) create a neutrino detector R&D area where detector prototypes could be exposed simultaneously to a neutrino beam and low-energy charged beams of (e, π, μ). The Physics reach and performance of the facilities has been the subject of several meetings organized within EUCARD/Neu2012 and summarized in a one-day workshop organized at CERN [12] and in the Task 3 report [13]. Here we will concentrate on the accelerator side, or neutrino source, options including highlights of the R&D efforts required for their realization.

2 The CNGS Facility

CNGS is the first long-baseline neutrino facility in which the measurement of the oscillation parameters is performed by direct observation of the tau-neutrino (ν_τ) appearance. It is using an intense muon-neutrino (ν_μ) beam ($10^7 \nu_\mu$/day) generated at CERN and directed towards two dedicated large and complex detectors, OPERA [14] and ICARUS [15], located 732 km away at the Gran Sasso National Laboratory (LNGS) in Italy.

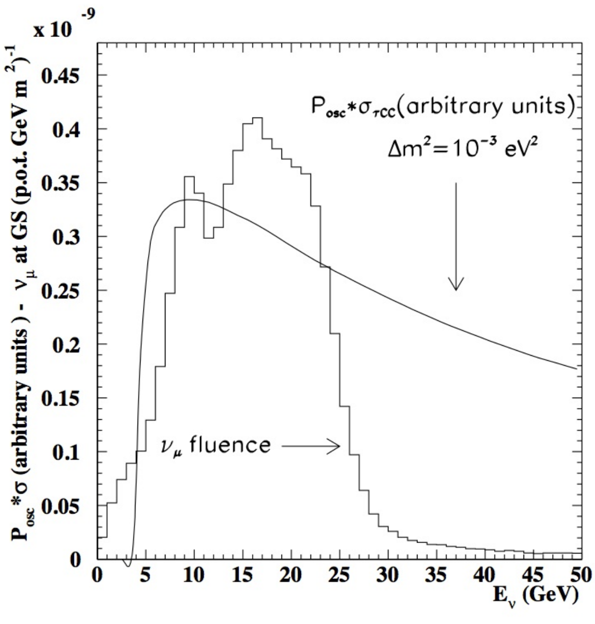

Figure 1: Expected ν_μ fluence spectrum at Grand Sasso, compared to the product of oscillation probability times ν_τ cross section.

The facility uses a 400 GeV proton beam which is fast extracted from the SPS and sent down an 840 m long proton beam line onto a carbon target producing secondary mesons (pions and kaons). The pions and kaons are energy-selected and using a horn and reflector as focusing elements guided in the direction of LNGS. They subsequently decay in a 1'000 m long, 2.5 m diameter vacuum tube into ν_μ and muons. By changing the sign of the electric field in the horn and reflector positive or negative hadrons can be focused, producing respectively a neutrino or anti-neutrino beam. A hadron stopper at the end of the decay tube absorbs the protons that have not interacted with the target and the secondary pions and kaons that have not decayed in flight. Only neutrinos and muons can traverse this 18 m long block of graphite and iron. Two muon detector stations measure the muons before they are absorbed further downstream in about 500 m of rock. The muon stations reside in two caverns separated by 67 m of rock. The average energy of the ν_μ that are sent to LNGS is about 17 GeV (see Figure 1). The layout of the CNGS facility is show in Figure 2.

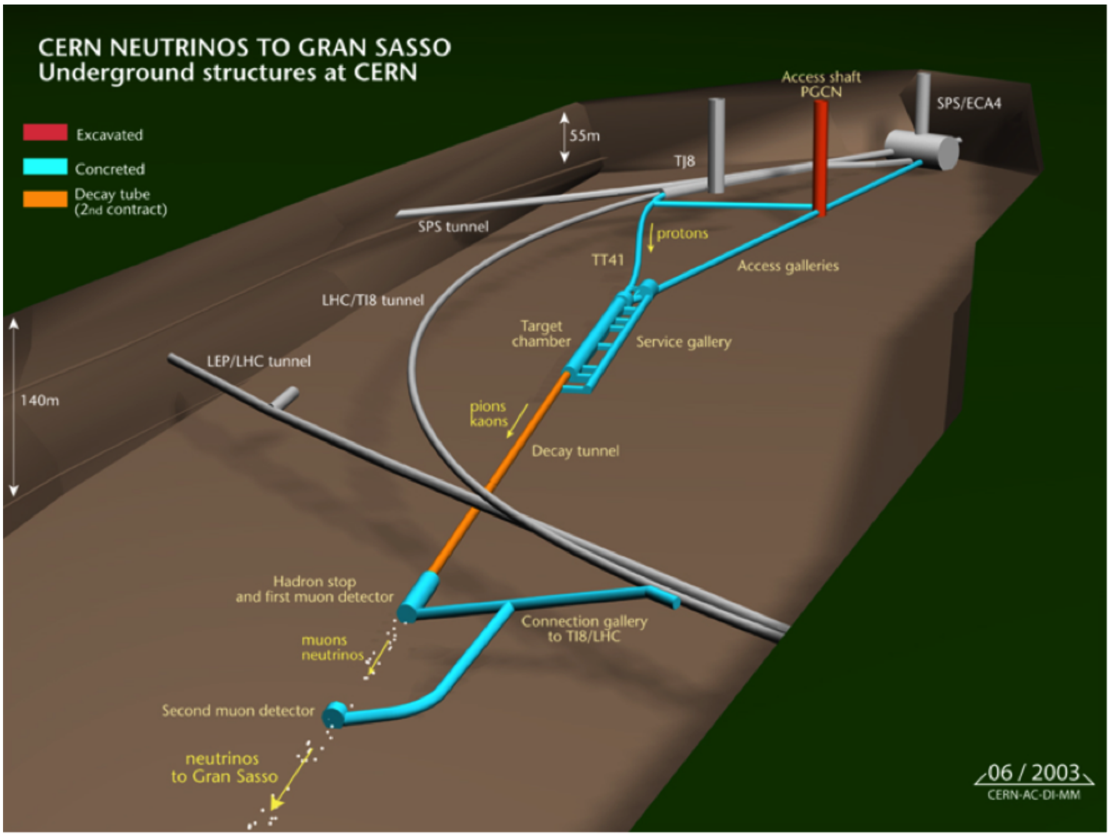

Figure 2: Layout of the CNGS underground structures at CERN where the neutrino beam is produced.

CNGS was commissioned in 2006 and following a slow startup due to early problems on the beam line equipment, the facility had five years of smooth operation until the end of 2012. In total, 1.824×10^{20} protons on target (pot), were accumulated during the CNGS operation, that corresponds to 81% of the design goal of 2.25×10^{20} pot. In Figure 3 the development of the integrated yearly and total statistics for the CNGS beam is shown. The record year for CNGS was 2011, where although running in parallel to LHC and the SPS fixed target program, 4.84×10^{19} protons on target were delivered, slightly beyond the expected 4.5×10^{19} from the project proposal.

The 400 GeV proton beam from SPS sent every 6 s to the target consists of two bursts of 10.5 μs with up to 2.25×10^{13} protons each, separated by 50 msec. The maximum beam power in dedicated mode of operation is 510 kW. In practice, however, the average beam power for CNGS is lower, approximately 300 kW. This is primarily due to intensity limitations in order to maintain the beam losses in the Proton Synchrotron (PS) and the SPS within the authorized limits, and secondly due to beam sharing in the SPS with the

LHC, the fixed target physics program and machine developments studies. In Figure 4 the configuration of the SPS super-cycle filled with only CNGS 6 s cycles is shown. Operating in such conditions with 100% beam time in SPS for CNGS was possible at the beginning of each physics period before the LHC and fixed target (FT) program started. In the case shown, the intensity per CNGS cycle is 3.8×10^{13}, corresponding to a beam power of 405 kW that is a world record for conventional neutrino beams.

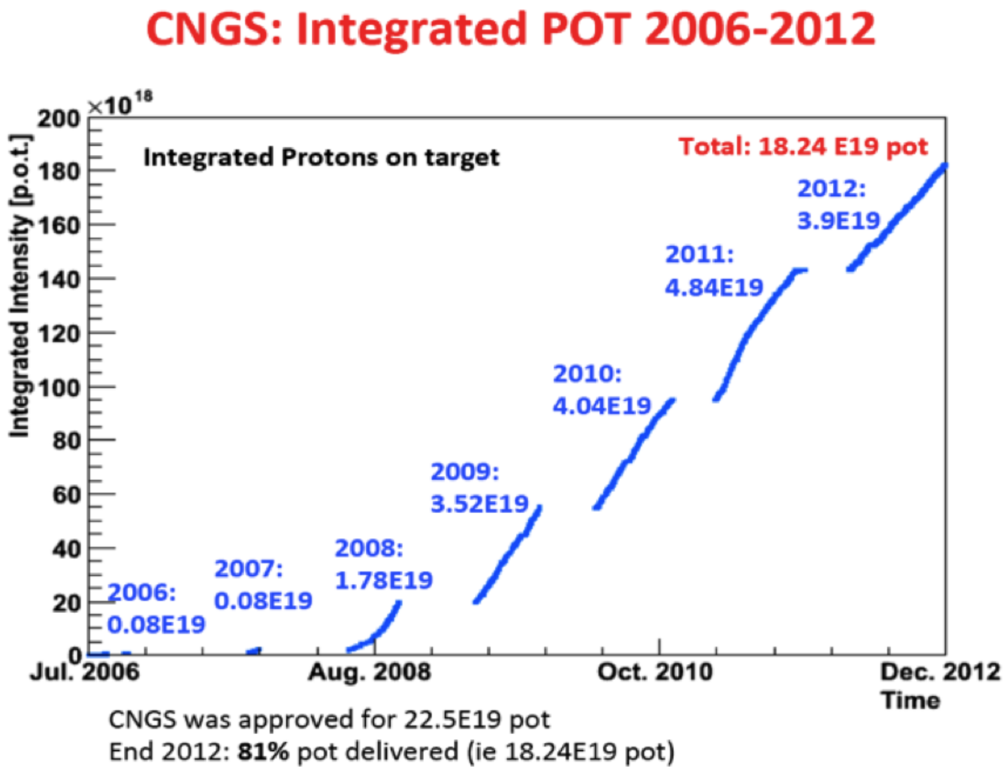

Figure 3: Integrated number of protons delivered from SPS to the CNGS target.

Operating this high-intensity, high-power facility regularly since 2006 proved to be rather challenging. Despite a careful design, initial failures in the secondary beam equipment had to be faced and relocation/shielding of service electronics had to be done. In multiple places, both in the target area and in the accelerators, mitigation measures had to be implemented [16].

Unfortunately the measured parameters of the neutrino mixing matrix and partially the lack of an easy near detector location do not favour the CNGS beam compared to other options for a future program. One proposal for a MODULAR [17] detector based on the ICARUS technology was presented and discussed in the Neu2012 meetings. The proposal considers two alternate sites close to the present LNGS location where large (20 kT) liquid Argon (LAr) detectors could be located made of blocks 5 kT modules "cloned" several times. The two detector locations are 10-15 mrad off-axis with respect to the CNGS direction. At this distance of ~ 730 km, the first $\nu_\mu \rightarrow \nu_e$ oscillation peak is around 2 GeV thus the present CNGS target and focusing system (horn and reflector) should be modified to provide focusing of low energy $7 - 20$ GeV pions (giving the right energy neutrinos in the off-axis beam), and with large angular acceptance.

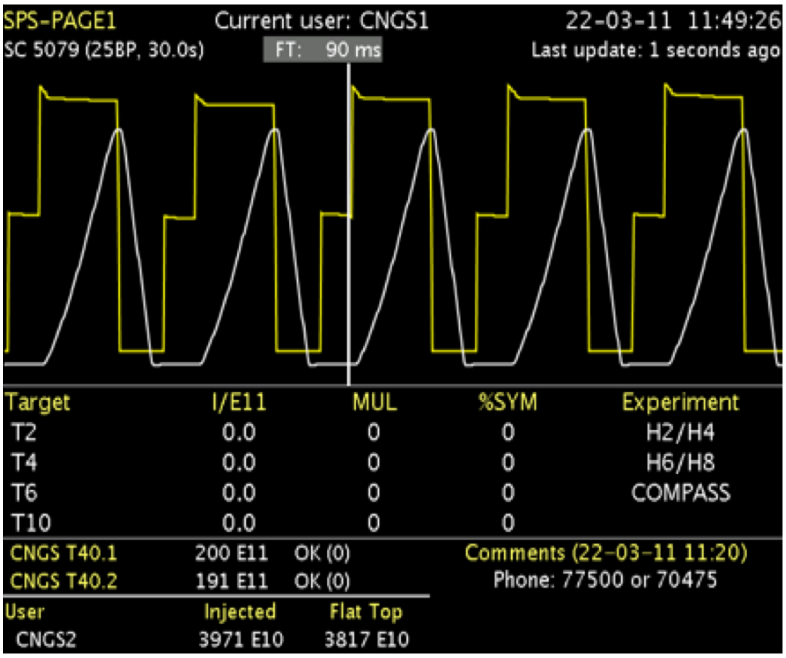

Figure 4: SPS super-cycle configuration with five 6 s *CNGS cycles, or 100% duty cycle of the neutrino beam.*

Modifying the target and focusing elements of the present CNGS secondary beam layout is rather challenging due to the radiation levels in the target hall after the five years of operation. In the present configuration where a high-energy neutrino beam is produced, the target and the horn are physically separated. An optimal low-energy configuration would require the target and horn to be close together and most likely the target partially of fully inserted into the horn that also increases the angular acceptace of the beam. New target and horn system optimized for the new layout could be designed to replace the existing equipment. However the engineering constraints are substantially different from the present situation, in particular if required to work at higher beam intensities than today. The removal of the existing equipment and installation of the new ones could be done in the major part remotely using the overhead crane. However a detailed study needs to be performed as even limited human intervention in the area would be rather penalized in terms of dose.

Besides the new target and focusing elements, the experiment requires a shorter decay pipe in order to reduce the ν_e background in the neutrino beam coming from the muon decays. This would be even more challenging as would require civil engineering works that can be prohibiting due to radiation doses around the decay pipe, as no remote operation may be feasible. Last but not least, the operation of the new beam, probably in view of increased intensity would require an update on the radio protection and environmental impact studies.

Presently this option is not further pursued. The construction and operation of the CNGS ν-beam has been a source of very valuable experience, which can be capitalized in the design of other conventional neutrino beams, presently pursued by the European Neutrino Community and presented in the next sections.

3 New Conventional Sub-MW Neutrino Beams from the CERN SPS

3.1 Short-baseline Neutrino Facility in the SPS North Area

The proposed SPS short baseline neutrino experiment in the North Area by the ICARUS and NESSiE collaborations [9], plans of using a proton beam extracted from the Long Straight Section 2 (LSS2), of the SPS, and transported via the existing Transfer Line TT20, to a new target cavern located underground close to the Target Area TCC2. The secondary neutrino beam will be of conventional design, like CNGS, but adapted to focus low-energy neutrinos. The expected proton flux is between 50 and 100% of the operational value of CNGS. Two detectors are foreseen: the T600 (600 t LAr imaging TPC) ICARUS module from Grand Sasso as far detector, and a T150 (150 t LAr "copy") as near detector. Both detectors are followed by magnetized spectrometers from the NESSiE collaboration, recuperated from the OPERA experiment. The layout of the facility is shown in Figure 5.

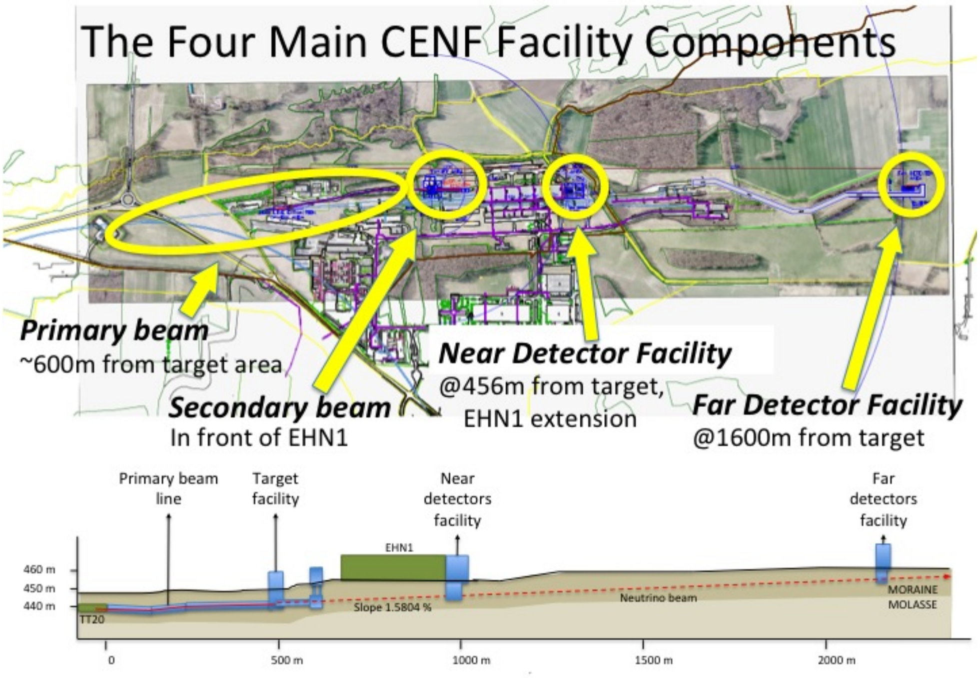

Figure 5: Layout of the SBLNF facility. The target cavern, the near and far detector locations, as well as the location for detector R&D at the end of the EHN1 experimental hall are indicated (from [18]).

Once build, the new beam line, named CERN Neutrino Facility (CENF), could be a suitable facility for testing in addition to the ICARUS, and NESSiE experiments other detector prototypes for future neutrino experiments. In the near detector location that will be located in an extension of the EHN1 experimental hall of the North Area, space is foreseen to house three, possibly four large neutrino detectors. The layout of the near detector location is shown in Figure 6. Downstream the ICARUS and NESSiE detectors, a test module for a future LAGUNA LAr detector is shown with a possibility of a fourth detector filling the empty space in front. The possibility to expose these detectors to a charged particle beam by extending one of the existing beam lines of the hall, makes this facility a unique test bed for the development of the next generation of neutrino experiments.

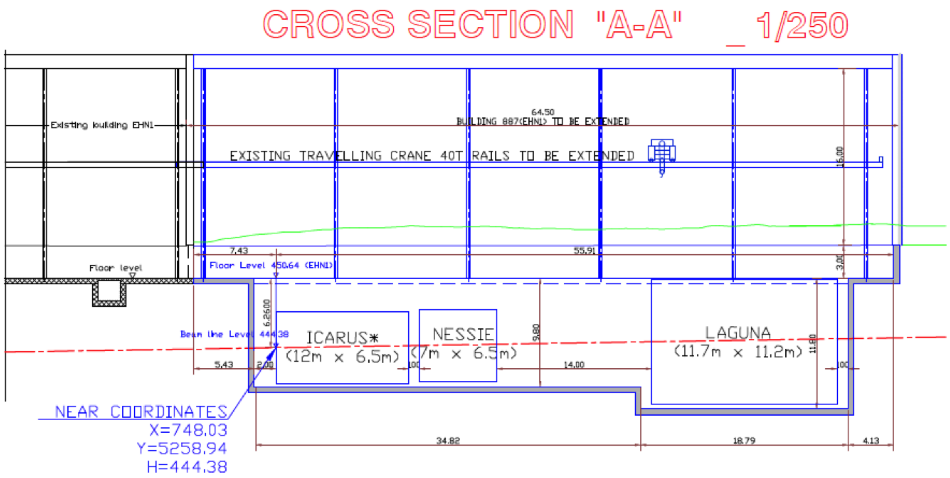

Figure 6: Layout of the CENF near detector location at the extension of the EHN1 experimental hall. The neutrino detectors will be located in a trench below the floor of the building on the neutrino beam axis. The ICARUS 150t detector is at the front, followed by the NESSiE spectrometer detector. The LAGUNA prototype (6 × 6 × 6 m) is located at the downstream end such that can also receive a charged particle beam from the H2 beam line.

The main parameters of CENF are shown in Table 1. The target cavern will be located at about 15 m below ground and will point slightly upwards (about 12 mrad) to center the beam at the far detector that will be at the surface. Due to the the shallow depth, the target, secondary beam elements and the decay pipe will be enclosed in a He tank to reduce the production of radioactive elements, as is done for the T2K beam. The design of the secondary beam elements: target and horns, will be based on CNGS, adapted to the new primary beam energy and focusing requirements to produce lower neutrino energy beam.

The primary proton beam for CENF requires a new fast extraction in the SPS LSS2 section. As space is not available in this straight section that already accommodates the slow extraction for the fixed target beams, a solution is found using the injection kicker at LSS1 to give an initial kick to the beam and then extract it at LSS2 as shown schematically in Figure 7 from [19]. This beam extraction scheme was tested with low-intensity beam in 2012 and seems to work with minimal losses due to the new beam trajectory in SPS. However It can only work for the 100 GeV SPS beam as required for CENF. For higher

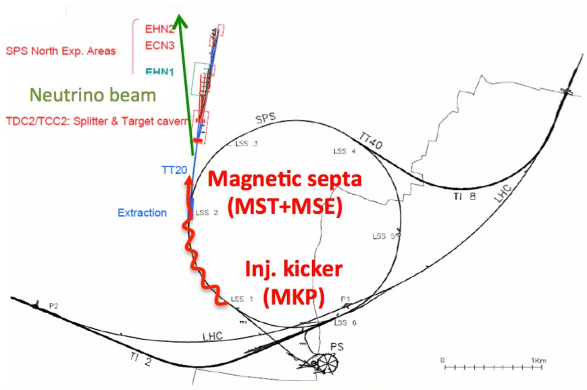

Figure 7: Schematic view of the extraction scheme for the short-baseline beam to the SPS North Area.

beam energies additional kickers from LSS6 can be used. Although in this extraction scheme for CENF minimal hardware modifications are required, the fixed-target and neutrino beams cannot operate simultaneously,. This because during the fast extraction the kicker and septum elements at LSS2 must be retracted to a position that assures the correct aperture and be protected in case of accidental beam impact. The movement and alignment of the septum cannot be done in pulse-to-pulse mode. A time-sharing mode is theerefore envisaged that could allow the neutrino experiments to take $3.5 - 4.0 \times 10^{19}$ protons on target per year, similar to what was delivered to CNGS, maintaining the fixed target program as present.

Parameter	**Value**
Primary beam momentum	100 GeV/c
Neutrino spectrum	$\sim$ 2 GeV
Beam intensity	3.5×10^{13} ppp (4.5×10^{13} ppp ultimate)
Cycle length	6 s (3.6 s min.)
Beam power	140 kW (200 kW ultimate)
Distances from target:	
Near detector	456 m
Far detector	1'600 m
Neutrino beam	1.5804%, 15.804 mrad upwards
Decay pipe	$\sim$ 100 m, 2 m diam.
Hadron absorber	10 − 18 m long
Installation depth	$\sim$ 11 m from ground

Table 1: Key parameters of the SBLNF beam from [18].

An LoI for the CENF facility was submitted to the CERN management in February 2013 [20] and is presently under consideration. The design study for CENF is on-going, and the project approval should happen in 2013 within the European Strategy process. The beam will be ready after three to four years, depending on availability of resources. To remain competitive for the physics program of the ICARUS and NESSiE experiments in the search of anomalous (sterile) neutrino oscillaitons the beam should be ready before 2017 to allow at least a year of physics run before the foreseen shutdown of the CERN accelerators for LHC upgrade.

3.2 Long-baseline Neutrino Facility in the SPS North Area

The Large Apparatus studying Grand Unification and Neutrino Astrophysics (LAGUNA) [21] study [1] investigated seven pre-selected underground sites in Europe (Finland, France, Italy, Poland, Romania, Spain and UK) capable of housing large volume terrestrial (or accelerator generated) or astrophysical neutrino detectors. The study was focused on geo-technical assessment of the sites, concluding that finally no show-stoppers exist for the construction of the required large underground caverns. The LAGUNA-LBNO FP7/EC-

[1] Design study funded by the European Commission via the FP7 program from 2008 to 2011

funded design study [5] extends the LAGUNA one in two key aspects: the detailed engineering of detector construction and operation, and the study of a long-baseline neutrino beam from CERN. For the accelerator based neutrinos it is proposed to construct a Long-Baseline Neutrino Oscillation (LBNO) beam facility having as an initial step a conventional neutrino beam based on the CNGS technology using an upgraded beam power from the CERN SPS. [5]

Based on the findings of LAGUNA study, the Pyhäsalmi mine in Finland is chosen 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. A cut view of the mine and the proposed layout for the LAGUNA detectors is shown in Figure 8.

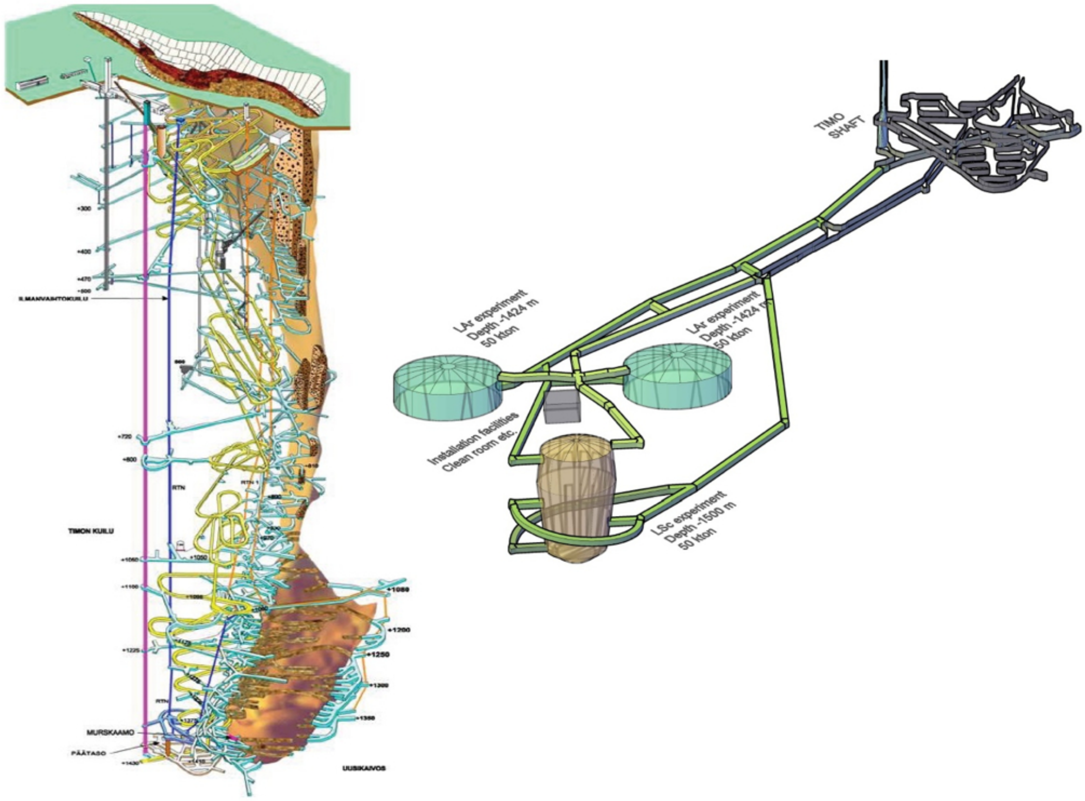

Figure 8: LBNO far site location: (left) Present layout of the Pyhäsalmi mine; (right) the additional underground infrastructure for the LAGUNA detectors to be constructed at the bottom of the mine at −1400 m*. The option with two* 50 kton *liquid argon detectors together with a liquid scintillator* 50 kton *detector is shown. (Courtesy LAGUNA-LBNO).*

The LBNO proposal includes two stages for the beam. In the initial stage, it is envisaged to operate at 750 kW of nominal beam power in a conventional beam design based on CNGS technology. Reaching the 750 kW of beam power in SPS goes beyond the record intensity ever achieved in the machine [22]. The present SPS performance for the LHC and CNGS-type beams as well as what would imply to reach the required power for a future neutrino program is given in Table 2. It is evident that achieving the required beam intensity would be very challenging. The record intensity of the CNGS beam of 565 kW was obtained during a machine development test in 2004, while in the normal CNGS physics production the machine was operated at max-470 kW of beam power. The difference comes to beam losses which for a short test were acceptable, even if occurred in practically all machines, while are unacceptable in steady operation. Expectations for the LHC beam are based on requests coming from the High Luminosity LHC (HL-LHC) [23] upgrade and considered as a stretched goal for the LIU project [4]. The last column of Table 2 indicates the SPS potential for the CNGS-type beam after the LIU campaign.

	OPERATION		**SPS RECORD**		**AFTER LIU(2020)**	
	LHC	CNGS	LHC	CNGS	LHC (aim)	post-CNGS (study)
SPS beam energy [GeV]	450	400	450	400	450	400
bunch spacing [ns]	50	5	25	5	25	5
bunch intensity [$\times 10^{11}$]	1.6	0.105	1.3	0.13	2.2	0.17
number of bunches	144	4200	288	4200	288	4200
SPS intensity [$\times 10^{13}$]	2.3	4.4	3.75	5.3	6.35	7.0
PS intensity [$\times 10^{13}$]	0.6	2.3	1.0	3.0	1.75	4.0
PS cycle length [s]	3.6	1.2	3.6	1.2	3.6	1.2/2.4
SPS cycle length [s]	21.6	6.0	21.6	6.0	21.6	6.0/7.2
PS beam momentum [GeV/c]	26	14	26	14	26	14
beam power [kW]	77	470	125	565	211	747/622

Table 2: Present and future SPS performance for a possible neutrino beam.

The main intensity limitations for the CNGS-type beams are related to beam loss and radiation issues in all machines, in particular in the PS during injection and extraction. Within the LIU project, upgrades and studies in the injectors are planned, however these are focused for the LHC beam that has different characteristics thus not directly beneficial for the CNGS-type beams. For example, the CNGS-type beams are injected from PS such to fill almost all the SPS ring with 4’200 bunches spaced at 5 ns, while for LHC the beam occupies a small fraction of the ring. Moreover, the CNGS cycle is must faster and more demanding in terms of RF power and voltage compared to LHC. In the SPS intensity limitations are also related to longitudinal beam instabilities leading to uncontrolled longitudinal emittance blow-up.

The on-going LIU study of the implementation of a 200 MHz RF system to double the RF power, should allow an increase of the beam current. The RF upgrade will also contribute to the SPS impedance reduction. Although the stability of the LHC beam can be significantly improved by deploying a new SPS optics with low transition energy ($\gamma_t = 18$), its use for the CNGS-type beam still needs to be verified. From measurements, the CNGS beam stability is not increased below transition and an updated scheme may require even higher RF voltage for the same longitudinal emittance. Detailed studies of the full performance potential are on-going, and will be reported at the end of the LAGUNA-LBNO design study in September 2014.

The layout of the CERN neutrino beam to Pyhäsalmi (CN2PY) located in the CERN North Area is shown in Figure 9. The primary beam from SPS beam is extracted from the TT2/TT20 channel and the target cavern is underground near the TCC2 target for the FT beams. To point to the far site in Finland, the CN2PY neutirno beam must point 10.4 deg downwards or in a slope of 18.1%! The decay pipe and the foreseen locations for the muon monitoring stations and the near detectors are also indicated.

Figure 9: A possible layout of the long-baseline neutrino beam to Pyhäsalmi (CN2PY) in the SPS North Area.

The 400 GeV beam from SPS is extracted using the non-local extraction scheme as for the CENF case, shown in Figure 7. Due to the high energy of the beam the additional kickers at LSS6 must be used together with the ones at LSS2. As for the 100 GeV case the electrostatic septum at LSS2 used for the FT slow extraction is retracted to a safe position and to assure the correct aperture for the beam. For the 400 GeV case of CN2PY, additional kickers must be installed at the LSS6 section. As shown in Figure 10, the beam is given an initial kick at LSS6 and then oscillates for 2.2 km before it reaches the LSS2 section where with a second kick is extracted to the TT20 channel towards the North Area. This novel extraction scheme was tested with real beams in SPS and seems to work. Further studies will be needed to fully validate this option for the foreseen high-intensity operation. [19].

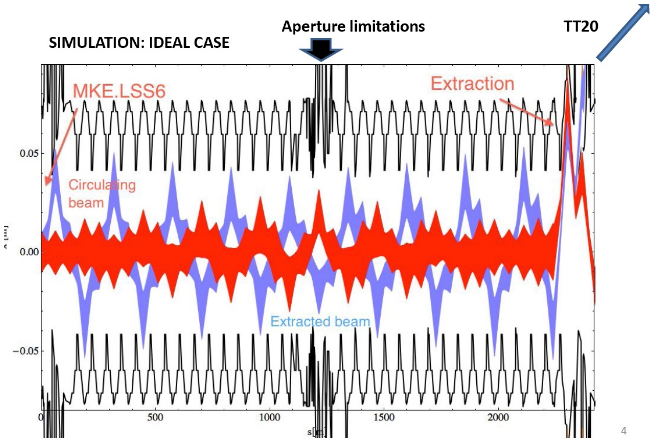

Figure 10: Schematic view of the non-local extraction scheme for the CN2PY beam beam from SPS.

The main parameters of the CN2PY beam are summarized in Table 3. In the table, the beam parameters for both proposed stages: using the 400 GeV beam from SPS at sub-

MW level and a 2=MW beam from a new high-power proton synchrotron (HP=PS) machine at 50(or 70) GeV as will be explained in the following section. The target cavern and secondary beam infrastructure is the same for both cases. However the target head, the focusing elements (horns) and muon stations will be optimized for each beam and most likely will be different. Key challenges in the neutrino beam design are the horns, that must be optimized to efficiently capture the low-energy secondary hadrons out of the target which most likely will be fully or partially inserted in the neck of the horn.

Parameter	**SPS beam**	**HP-PS beam**
Primary beam momentum	400 GeV	$50 \div 70$ GeV
Beam intensity	7×10^{13} ppp	$2.5 \div 1.7 \times 10^{14}$ ppp
Cycle length	6 sec	1 sec
Beam power	750 kW	2 MW
Distances from target		
Near detector	800 m	
Far detector	2300 m	
Neutrino spectrum		
1st osc. max.	$3 \div 4$ GeV	
2nd osc. max.	$1 \div 2$ GeV	
Neutrino beam	10.4 deg downwards	
Decay pipe	400 m	

Table 3: Key parameters of the CN2PY beam.

3.3 Technical Synergies Between Short and Long Baseline Facilities in the SPS North Area

The two proposals for short and long-baseline build on the CNGS experience, share common technology developments and due to the different timescale for physics can be considered as part of a common, staged program. The common technology developments include the fast extraction from SPS via the LSS2 section and the beam transfer in the TT20 line, and more importantly the development of low-energy neutrino beams from the 100 or 400 GeV beams from SPS. In Figure 11 the muon neutrino spectra for the CENF beam and the one required for the LAGUNA CN2PY long-baseline beam are shown.

In both cases low neutrino beam energies, in the range up to 10 GeV have to be developed, much lower compared to CNGS. Interesting enough, the central neutrino energy for the short baseline beam almost coincides with the required energy for the second oscillation maximum of the long-baseline beam. In both cases the low-energy ν-beam optimization is achieved by using a larger diameter horn with the target fully or partially inserted in its inner diameter. The whole target and horn geometry layout and focusing optics is further optimized to achieve the wanted neutrino beam spectrum for each beam, as shown in the CN2PY graph. What would be different in each case would be the engineering and more importantly the supporting services due to mainly the different slope

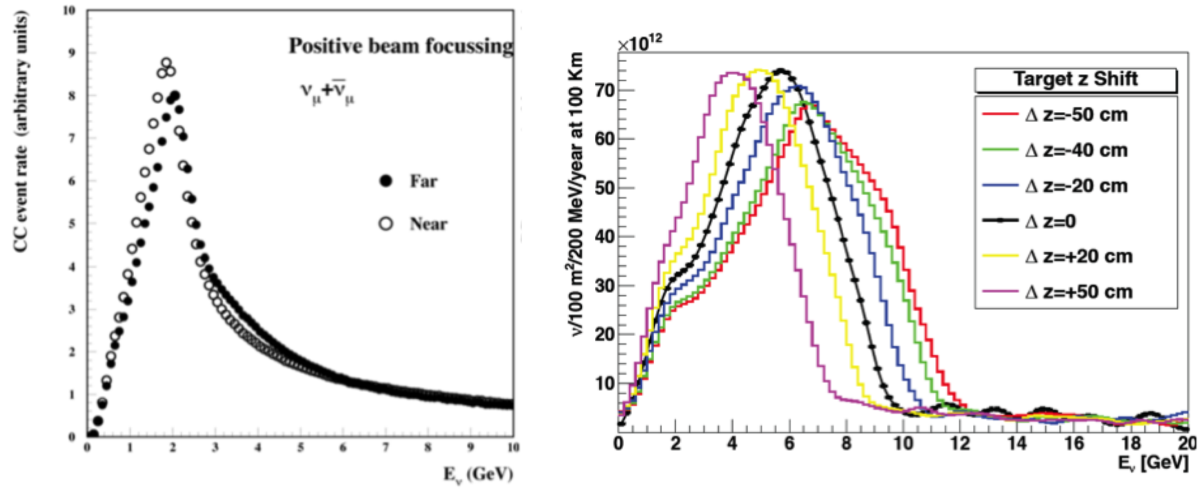

Figure 11: Left: muon neutrino CC interaction spectra at the near and far detectors for the short-baseline beam for a 100 GeV *primary proton beam. Right: Muon neutrino spectra at the far detector of the long-baseline beam for a* 400 GeV *incident proton beam on target.*

and depth location, but globally lot of technology could be shared and many common components and implementation ideas could be developed.

The short-baseline beam could serve as test beam for calibrating large-scale prototypes of the multi-kton detectors foreseen in the long-baseline beams. In addition important physics quantities like cross-sections that enter in the neutrino oscillation measurements could be performed, which would help in reducing the systematic errors involved. The detector prototypes could also receive low-energy charged particle beams from the existing secondary beams available in the North Area, essential to understand the performance of these detectors and extrapolate to much larger volumes.

4 Long Term Prospects

Multiple long-term options have been proposed and discussed for neutrino physics in Europe. All have in common that they try to profit and maximize the use of existing facilities at CERN. The beam presently available from SPS keeps the record of the high-intensity world-wide. Its potential upgrades after LIU and most importantly the possibility for CERN to construct a high-power version of the Super-Conducting Proton Linac (SPL) [24] at the extension of LINAC4, are important assets for the lab where these options are based. These long-term options were studied in detail in the EUCARD and LAGUNA-LBNO design studies, presented in the various EUCARD/Neu2012 meetings and workshops. Highlights of the design layout and parameters for thee are presented here.

4.1 High-power (2 MW) Upgrade for the Long-baseline Neutrino Beam

For the second phase of the CN2PY beam studied in LAGUNA-LBNO a new 2 MW 50 GeV proton driver is being considered. This new accelerator would be used to prepare the proton beam to the same target area which would be designed already from the first phase to accept the increased beam intensity. The High-Power Proton Synchrotron (HP-PS) would have the Low-Power SPL (LP-SPL) as H^- injector. The HP-PS machine is designed having in mind the neutrino beam, although the possibility to be used as injector to SPS replacing at that time the PS and PSB that despite the present renovation would be close to 65-years old, would not be neglected.

A tentative set of parameters for the HP-PS machine is presented in Table 4. Two options are considered for the final top energy: 50 GeV and 75 GeV. In both cases the full potential of the LP-SPL is used to deliver the required intensities. The repetition rate is 1 Hz in both cases, where the higher energy of the 75 GeV option helps to reduce the beam intensity at the penalty of higher ramp rate for the magnets. For both options superferric magnets similar to the one designed for the FAIR [25] project could advantageously be used, instead of normal conducting (resistive) magnets. Fro the lattice a 3-fold symmetric with resonant Negative Momentum Compaction (NMC) arcs, which avoid transition. Doublet cells can be considered for long uninterrupted straight sections, which can house independently injection with collimation, extraction and RF equipment.

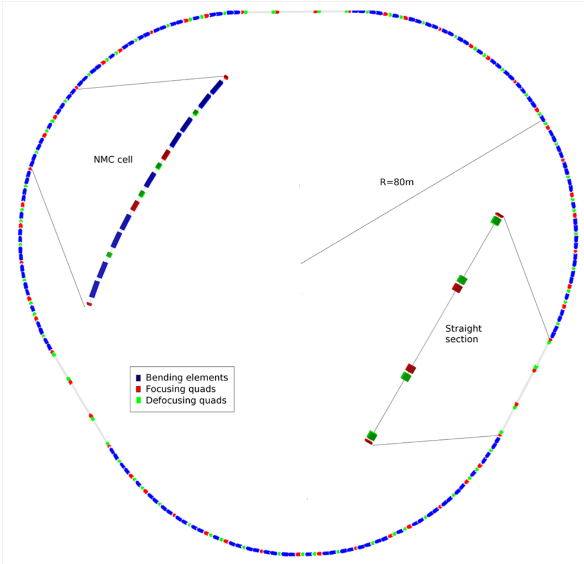

Figure 12: Schematic view of the HP-PS ring lattice. The three straight sections for injection, extraction and RF acceleration are visible.

Paramater	50 GeV	75 GeV	**Units**
Inj.Extr. Kinetic Energy	4/50	4/75	[GeV]
Beam Power	2		[MW]
Repetition Rate	1		[Hz]
f_{rev}/f_{RF} at inj.	0.248/38.97		[MHz]
RF harmonic	157		-
f_{rev}/f_{RF} at extr.	0.255/40.08	0.255/40.09	[MHz]
Bunch spacing at extr.	25		[ns]
Total beam intensity	$2.5\,10^{14}$	$1.7\,10^{14}$	-
Number of bunches	147		-
Intensity per bunch	$1.7\,10^{12}$	$1.25\,10^{12}$	-
Main dipole field inj./extr.	0.17/2.1	0.17/3.13	[T]
Ramp time	500	500	[ms]
Dipole field rate dB/dt (acc. ramp)	3.9	5.9	[T/s]

Table 4: Basic design parameters for five options of the HP-PS machine

Besides the magnet design, the RF and collimation systems are additional design challenges for the HP-PS. The conceptual design of the accelerator along with its injection/extraction beam transfer lines to the CN2PY target will be further studied within the LAGUNA-LBNO design study.

4.2 Neutrino Factory

4.2.1 Baseline Layout

The International Design Study for a Neutrino Factory (IDS-NF) [26] collaboration and the WP3 of the EC-funded FP7 EURONU have studied the feasibility of a neutrino factory using 25 GeV neutrinos sent in two storage rings to two distant detectors at 4'000 Km and 7'500 Km. The recent measurement of θ_{13} has a decisive impact on the choice of future neutrino experiments and opened the possibility to discover CP violation in the leptonic sector using a low-energy neutrino factory as the best facility for probing this physics. Using the neutrino flux from the decay of 10^{21} muons/year in a 10 GeV storage ring, the neutrino factory is a competitive option for an about 2'000 km baseline, for a measurement of the CP-violation phase and the neutrino mass hierarchy and further precision measurements in the neutrino sector. This downscaled neutrino factory with a single ring and low-energy comes at a reduced cost and complexity yet maintaining the required physics reach and sensitivity. This new baseline layout differs from the one previously studied mainly in the muon acceleration systems and the presence of a single decay ring.

A possible implementation of this facility at CERN is shown in Figure 13. The 4 MW proton beam is produced by the high-power SPS (HP-SPL). HP-SPL is a ~ 500 m long, 5 GeV SPL, supplying a minimum of 10^{14} protons in beam pulses of 0.4 ms at a repetition rate of 50 Hz. It uses LINAC4 as front-end, upgraded to pulse at that rate. For the Neutrino Factory, HP-SPL is is followed by an accumulation ring and a compression ring to form 240 μs long proton pulses composed of three bunches of 3 ns (rms) each. This intense proton beam is directed towards a liquid mercury target to produce secondary mesons that subsequently decay into muons. The pions generated by the proton beam in the mercury target are captured by a 20 T to 1.5 T solenoid tapering field and decay channel. At the end of the decay channel an intense muon beam is produced.

A sophisticated bunching and bunch rotation scheme is applied to reduce the muon energy spread, followed by an ionization cooling channel in order to transfer the muon momentum in the longitudinal plane. The resulting beam is accelerated first by a linac and then by two Recirculating Linac Accelerators (RLAs) to reach the final energy of 10 GeV. Alternatively the second RLA could be replaced by a Fixed Field Alternating Gradient (FFAG) ring. Muons are then injected in a decay ring with two straight sections pointing in the direction of a far detector located at a distance of $\sim 2'000$ km.

4.2.2 Specific R& D Subjects

- **Pion production and target focusing**: Although encouraging results were obtained by the MERIT [27] experiment, major issues remain to be addressed in the design of a mercury target able to withstand a multi-MW proton beam. Solid targets made up of packed spheres or powder represent an alternative solution which is favoured by the future generation of conventional beams, where up to 1 MW proton

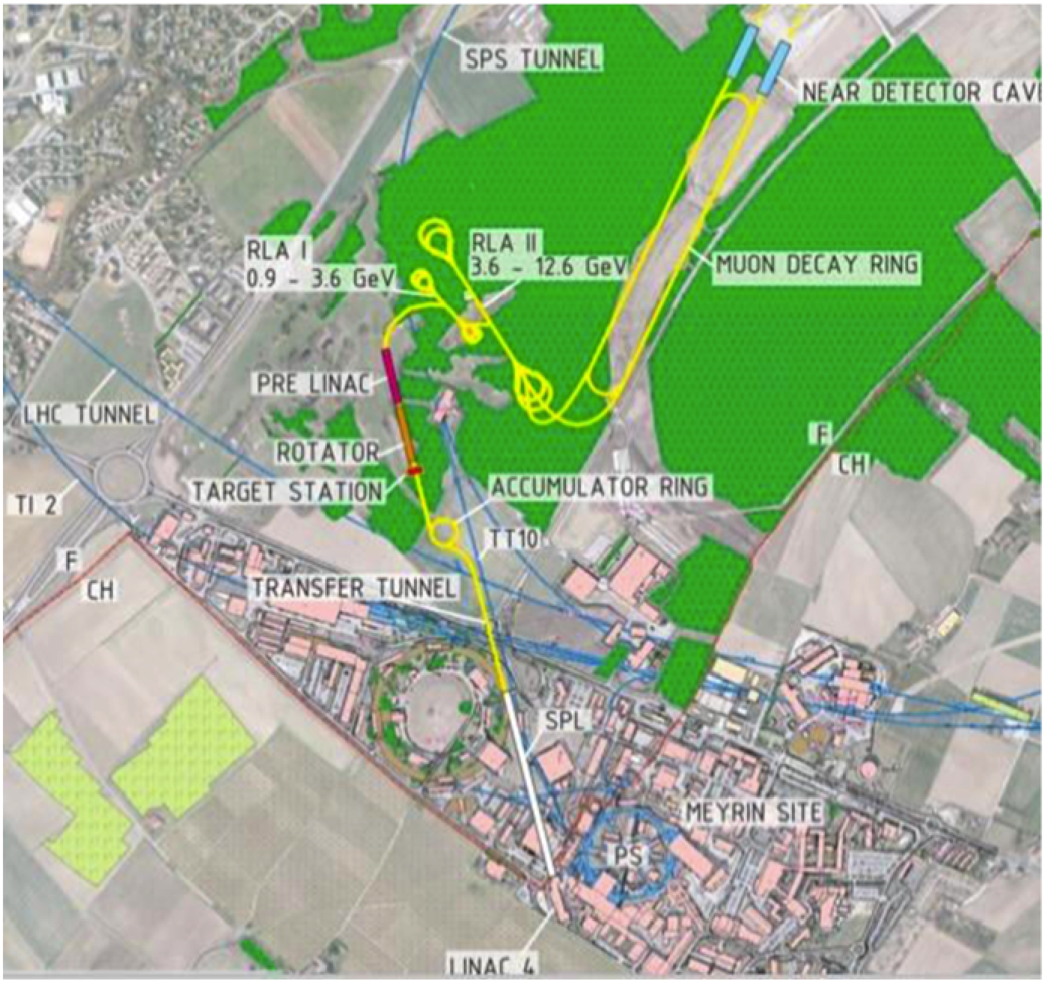

Figure 13: A possible layout of the low-energy neutrino factory at CERN (Courtesy: A. Kosmicki, J. Osborne and C. Sinead Waaijer).

beams will be used. The CERN HiRadMat facility [28] will be very useful for testing possible target prototypes.

- **Ionization cooling channel**: The muon ionization-cooling channel is a fundamental part of the neutrino factory. The MICE [29] experiment, currently in operation at the Rutherford Appleton Laboratory (RAL, United Kingdom) should measure for the first time, muon ionization cooling thanks to two cooling cells, as proof of principle that this channel can be effectively be built. The experiment foresees several staging phases with increasing complexity and is expected to produce its final results in four to five years from now. The performance of such a cooling channel depends on the maximum RF gradient that can be achieved in the presence of strong magnetic fields. The findings in the MICE experiment will determine the operational limits and performance of a possible cooling channel in a neutrino factory.
- **Muon acceleration**: In the proposed baseline, muons are accelerated via a linac and two RLAs (or one RLA and one FFAG ring). The accelerating system is composed of focusing quadrupoles and 200 MHz super conducting RF cavities where CERN could play an important role due to the available expertise. The FFAG option is also of interest and is being tested in the EMMA ring [30], at the Daresbury Laboratory

(United Kingdom), however only with electrons and not with protons or muons.

- **NuSTORM project**: A very simplified version of the neutrino factory called NuSTORM has been recently proposed [31] as a prototype milestone. NuSTORM basically consists of the target and decay ring of the neutrino factory: the pions produced at the target are captured using a horn and injected directly to the decay ring where decay into muons at the first straight section. NuSTORM could be an interesting alternative for a short baseline beam for the search of sterile neutrinos or cross-section measurements of the neutrino interactions, The facility proton driver, in case it would be placed at CERN could be the PS or SPS today or the HP-PS in the future. The energy of the stored muons will be limited to 2-4 GeV depending on the design considered. The target station would be a simplified version of the target system proposed for the neutrino factory at the $100 - 200$ kW range. NuSTORM is presently proposed for the FNAL using the protons from the main injector, and later could evolve to accommodate a muon cooling channel stepping towards a neutrino factory. Recently the possibility to implement the NuSTORM at CERN coupled to the short baseline neutrino detectors is invesigated and a Letter of Intent was submitted to the CERN SPS Committee, presently under considereation [32]

5 Other Long-term Alternatives

Within the EUROnu FP7/EC study alternative options for medium-baseline neutrino beams were studied. These included a CERN to Frejus (France) Super-beam, and a $\gamma = 100$ β-beam for the same baseline. Their physics reach and cost have been investigated together with that of a low-energy (10 GeV) Neutrino Factory as presented above. From the study, the physics performance of the Neutrino Factory is superior than the other options and therefore preferred despite its higher cost. Nevertheless, the Super-beam and β-beam options when coupled to a large water Cherenkov (500 kt MEMPHYS [33]) detector offer interesting capabilities and could remain competitive to the other long-baseline options, therefore included here for completeness.

5.1 A Beta-beam

5.1.1 Baseline Layout

The beta-beam concept [34] is of high interest in the CERN context because of the possibility to make use of a significant part of the existing accelerator complex. Research efforts during the past 10 years with the support of the EC-funded FP6 EURISOL design study [35] and FP7 EUROnu WP4, allowed to make decisive progress on the technical feasibility of the proposed baseline ions (^{6}He and ^{18}Ne up to $\gamma = 100$). The produced pure ν_e and anti-ν_e beams are directed towards large (three 400 kt) underground Water Cherenkov detector located in the Fréjus underground laboratory in France, at 130 km distance from CERN.

In order to enhance the physics reach, higher neutrino beams energies would be necessary which could be achieved with isotopes of higher Q values such as ^{8}Li and ^{8}B or with a new and higher energy SPS. A sketch of the β-beam facility studied so far is given in

Figure 14. The β-beam has to run in the CERN PS/SPS complex for ten years and be compatible with other physics programs at CERN. For this reason the favored proton driver for baseline ion production would be a high power version of LINAC4 or a dedicated new linac. The realization of the β-beam, relies on key R&D results, the ongoing activities and

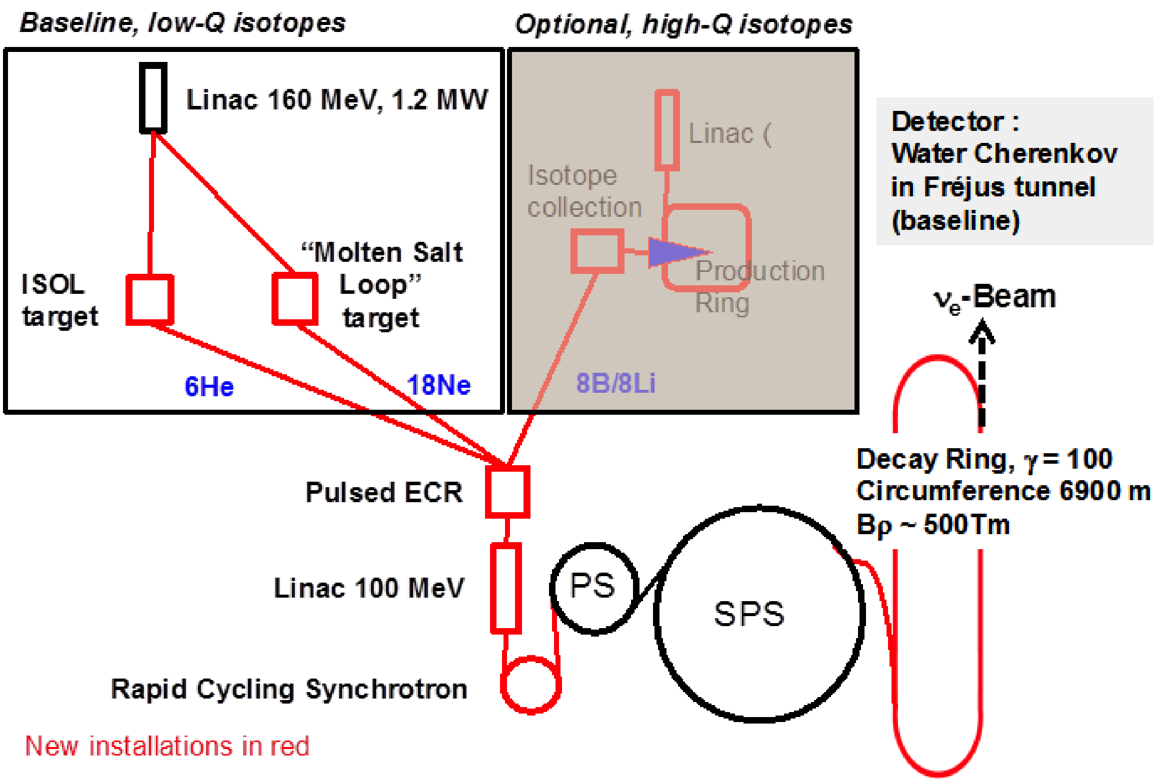

Figure 14: Schematic layout of the beta-beam facility. The two baseline options corresponding to the different isotopes.

prospects are outlined below:

- **Isotope production**: The conceptual design of a molten salt loop target using a 7 mA, 160 MeV proton beam to produce ^{18}Ne ions has been successfully validated at CERN at the ISOLDE [36] facility. A circulating molten metal target prototype will be operated at ISOLDE as part of the R&D for the next generation of radioactive ion beam facility EURISOL, thus being an additional step validating this design study. In addition, multiple prototyping activities relevant for isotope production will take place in the coming years with several tests of 50 – 200 kW neutron spallation source concepts dedicated for the production of radioisotope beams at TRIUMF (Canada) and SOREQ (Israel) laboratories. This would match the requirements for ^{6}He production.

  Significant advances have been made on the production of high-Q isotopes with the required experimental determination of reaction cross-sections and first steps towards the design of a collection device. The so-called direct production base on a high-power Li flowing film target is favored at present. Developments at the Argonne National Lab (ANL, United States) for the Facility for Rare Isotope Beams (FRIB) and the SOREQ Applied Research Accelerator Facility (SARAF) are on-going and will provide useful input on its technical feasibility.

- **ECR source**: R&D for a 60 GHz ECR ion source is actively pursued by the Laboratoire de Physique Subatomique et de Cosmologie (LPSC, France) and the Laboratoire National des Champs Magnetique Intenses (LNCMI, France). First tests at 28 GHz are ongoing and results are expected soon provided the funding support is assured.
- **RFQ and linac**: The 100 MeV/u ion linac would need two RFQs for pre-acceleration of the two ion species ^{18}Ne1+ and ^{6}He1+ up to a stripping device before entering the linac part at 0.46 MeV/u. A design of such an ion linac is available [37].
- **RCS**: The beam from the ion linac is multi-turn injected into a Rapid Cycling Synchrotron (RCS) pulsing at 10 Hz, then further accelerated to the PS injection energy, which would be 2 GeV instead of the 3.5 GeV assumed for the EURISOL design study. This would allow to match the present LIU specifications.
- **PS and SPS**: The studies and upgrades which will be implemented during LIU will significantly ease the acceleration of beta ions. Additional equipment will however still be needed, such as additional RF systems in the SPS, in order to prepare the beam for the merging at injection into the decay ring. Moreover, solutions for reducing collective effects and minimizing beam loss at high bunch intensities still remain to be found. The Linac3-LEIR chain could advantageously be used for testing various schemes envisaged in the PS and SPS.
- **Decay Ring**: The Decay Ring is the main cost driver in the beta beam facility. A merging system is necessary to meet the bunch length requirement for background rejection in the detector. Collimation of a large part of the beam is necessary. The superconducting 6 T magnets would have an open coil in the mid-planes. The Decay Ring optics has also been changed to handle Transverse Mode Coupling Instabilities (TMCI). The beam time structure along the whole accelerator complex remains to be optimized.

5.2 Super (4 MW) ν-Beam

5.2.1 Baseline Description

The neutrino Super-Beam is a conventional ν-beam as described in the sections above, but with a high-power typically of multi-MW power primary proton beam. This setup can produce very high fluxes of neutrinos of low-energy (basically due to the limitations of the proton drivers to produce high-power at high energies) adequate for medium baseline neutrino oscillation experiments. The Super-beam configuration studied in EUROnu aims at producing a neutrino beam to large water Cherenkov detectors located at the Frejus underground laboratory in France at 130 km distance from CERN. As proton driver the HP-SPL as described above is assumed providing a primary proton beam of 4 MW of power.

Downstream the HP-SPL an accumulator ring will collect several linac pulses and then fast extract them towards the neutrino beam target. The neutrino beam has the same configuration as in conventional beams with one noticeable exception: the target and horn design that is a block of four units instead of one, as shown in Figure 16. This because presently no solid target solution is available for beam powers exceeding the 1(possibly 2) MW. The solution of an open loop liquid mercury target as proposed and validated

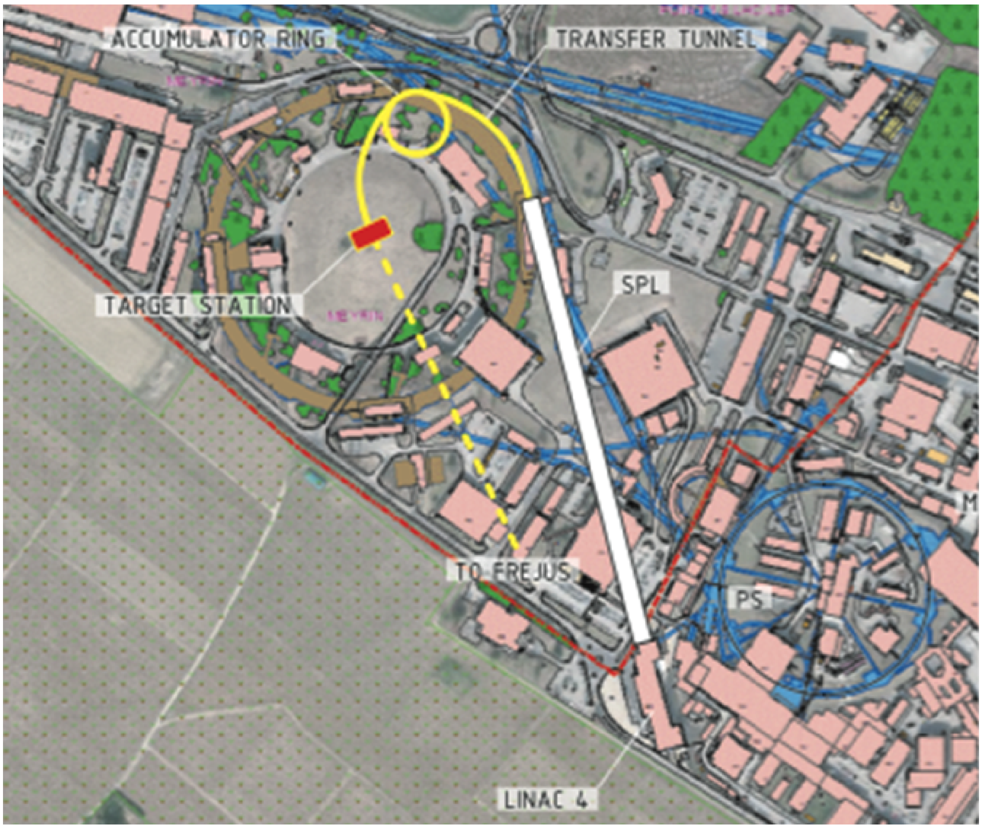

Figure 15: Possible layout of a medium energy super beam facility at CERN - (Courtesy A. Kosmicki, J. Osborne and C. Sinead Waaijer).

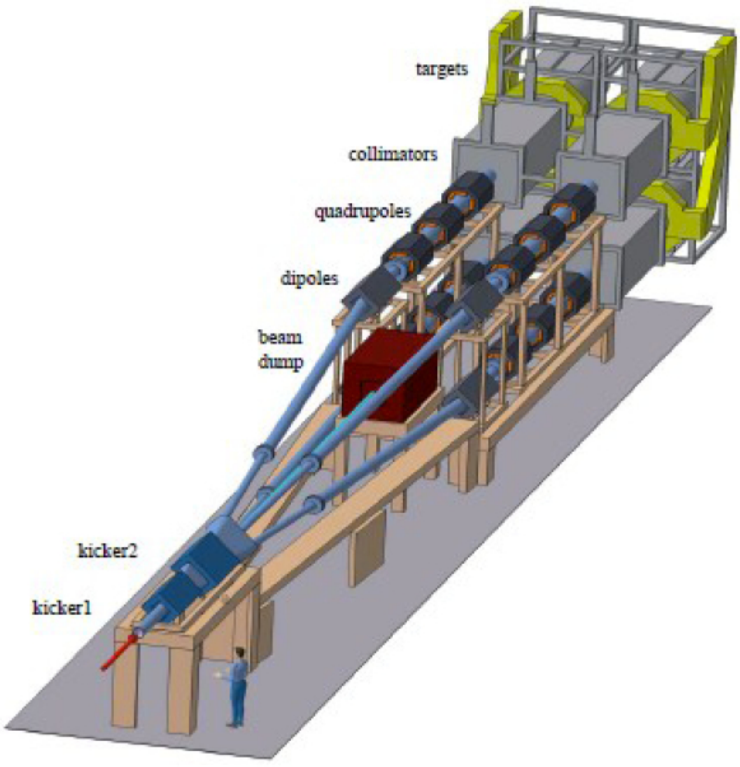

Figure 16: Schematic view of the SB target station with the four 1 MW target/horn assemblies and teh beam switchyard upstream - (Courtesy M.Dracos, EUROnu/WP2).

for the Neutrino Factory could be envisaged, but it involves serious safety concerns and rather complicated systems. So instead, using a beam switching layout upstream, the beam is delivered in four targets each one receiving about 1 MW of beam power.

6 Summary

Neutrino physics continue to be an exciting area for research in particle physics. The opportunities for discoveries of key parameters of the underlying theory in the neutrino sector is very intriguing and a variety of proposals for accelerator made neutrino oscillation experiments are under study. CERN's existing facilities are an important asset for hosting or developing the technology for these future neutrino beams. SPS is identified as a key machine in several neutrino beam projects in the near future. Its demonstrated capability of delivering ~ 500 kW of beam power and possibly after some upgrade reach the ~ 750 kW level should be maintained including of course all the injector chain upstream.

In the short and medium term, the existing accelerators, especially after their foreseen upgrade, can potentially be used for conventional neutrino beams produced via pions decay. For the longer term, there are numerous scenarios where the participation of CERN in collaborative R&D would accelerate the pace of progresses. This is notably the case of the SPL technology that could be used for the different proton drivers options envisaged for the future facilities. The choice of the scenarios to be pursued shall ideally be driven by a roadmap promoted by the community of the physicists interested in neutrinos.

This report is based on the paper submitted as contribution to the Open Symposium of the Europen Strategy Preparatory Group meeting at Krakow. [38]

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