

CERN HIGH-POWER PROTON SYNCHROTRON DESIGN STUDY FOR LAGUNA-LBNO NEUTRINO PRODUCTION

R. Steerenberg, M. Benedikt, I. Efthymiopoulos, F. Gerigk, Y. Papaphilippou, CERN, Geneva, Switzerland

Abstract

Within the LAGUNA-LBNO project, CERN has started a high-power proton beam production design study for producing neutrinos. This study foresees a staged approach starting with a study to evaluate the feasibility of a CERN SPS accelerator intensity upgrade to increase the beam power from the existing 500 kW, presently available to CNGS, to 750 kW.

The final stage consists of a conceptual design study for a 30 – 50 GeV, 2 MW protons synchrotron, with the LP-SPL as injector. This paper will provide an overview of the project and then concentrates on the preliminary ideas for the HP-PS.

THE LAGUNA-LBNO PROJECT

LAGUNA-LBNO [1][2], which is a European FP7 design study, stands for Large Apparatus studying Grand Unification and Neutrino Astrophysics and Long Baseline Neutrino Oscillations and aims at answering fundamental questions on particle and astroparticle physics by developing the next generation of very large volume underground detectors, used to detect besides cosmic neutrinos also neutrinos coming from a high-power protons based neutrino production facility at CERN.

The study that runs from 2011 until 2014 investigates in more detail two sites: The shortest baseline from CERN, Frejus at 130 km from CERN and the longest baseline, Pyhäsalmi in Finland at 2300 km. The study is composed of 5 work packages, which are subdivided in tasks.

Table 1: LAGUNA-LBNO WP4 Tasks

| Task | Brief task description |
|------|--|
| 4.1. | Study of impact of CERN SPS accelerator intensity upgrade to neutrino beams. |
| 4.2. | Assessment of intensity upgrade of CNGS facility. |
| 4.3 | Conceptual design of the CN2PY neutrino beam. |
| 4.4 | Feasibility study of a 30 - 50 GeV High-Power PS. |
| 4.5 | Definition of the accelerators and beam lines layout at CERN. |
| 4.6 | Study the magnetic configuration for the LAGUNA detector. |
| 4.7 | Definition of near detector requirements and development of conceptual design. ¹⁾ |

¹⁾ The University of Geneva is responsible for this task.

CERN is responsible for work package 4, Long base line neutrino beam prospects and scenarios for detector

magnetization, and thus leads the task on the feasibility study of a 30–50 GeV High-Power Proton Synchrotron (HP-PS). This is intended to be the high-power and high-energy proton source for the CERN to Pyhäsalmi (CN2PY) facility, which itself is a task within WP4. The tasks within WP4 are summarized in Table 1.

HIGH BEAM POWER FACILITIES

The majority of the operational high proton beam power facilities are low energy facilities that produce intense beams in combination with high repetition rates.

SNS, in Oak Ridge USA, delivers about 1 to 1.4 MW beam power, through a LINAC and proton accumulator, at 1 GeV to a spallation target with a 60 Hz repetition rate. Increasing the energy out of the LINAC by 30% to 40% and intensifying the peak current from the H LINAC by approximately 50%, should bring the beam power up to 3 MW [3].

ISIS, at RAL in Oxfordshire UK, uses a similar production scheme with a LINAC, accelerating H⁺ ions up to 70 MeV followed by an RCS that increases the beam energy up to 800 MeV at a rate of 50 Hz, delivering 0.2 MW beam power [4]. An upgrade to a beam power of about 1 MW, using a new 3.2 GeV RCS has been studied, but more ambitious upgrades into the range of 2 – 5 MW beam power have been addressed too [5]. In many of the options discussed, the energy of the RCS is a main parameter together with an increase in beam intensity to reach higher beam powers.

However, few facilities produce high beam power with lower repetition rate and higher energies.

J-PARC [6][7], in Tokai-Mura Japan, is providing besides a high-power beam at 3 GeV, for neutron production, also a high-power and high-energy beam for the hadron hall experiments or the neutrino production for the T2K experiment. The LINAC currently operates at 180 MeV with a beam current of about 30 mA. A nominal LINAC energy of 400 MeV and a beam current of 50 mA, together with the 25 Hz RSC at 3 GeV, should provide a beam power of about 1 MW. The Main Ring that is currently operating at 30 GeV instead of the nominal 50 GeV should then produce a beam power of 0.75 MW at a rate that lies around 0.3 Hz.

CERN, Geneva Switzerland, produces presently a beam power of 0.5 MW out of the SPS for the neutrino production to Gran Sasso [8]. A 400 GeV proton beam at a maximum repetition rate of 6 seconds produces the high beam power. The LAGUNA-LBNO study addresses a possible upgrade of the beam power up to 0.75 MW, mainly through an increase of the beam intensity, as the repetition rate is already at the limit.

PRELIMINARY HIGH-POWER HIGH-ENERGY ACCELERATOR LAYOUT

The feasibility study for the HP-PS will partly be based on the PS2 study [9], but is dedicated to the production of protons to the CN2PY facility. The HP-PS is intended to use the Low Power Superconducting Proton LINAC (LP-SPL) [10] as injector.

One of the preliminary ideas on the possible staged implementation of the LP-SPL, HP-PS and CN2PY neutrino facility is given in Fig 1. At a first stage, the CN2PY facility could be fed by the beam from the SPS, provided a new transfer tunnel and beam line is constructed. In a second stage, upon completion of the LP-SPL and HP-PS, the HP-PS beam should also be transferred to the CN2PY facility, increasing the beam power on target from 0.5 or 0.75 MW to 2 MW.

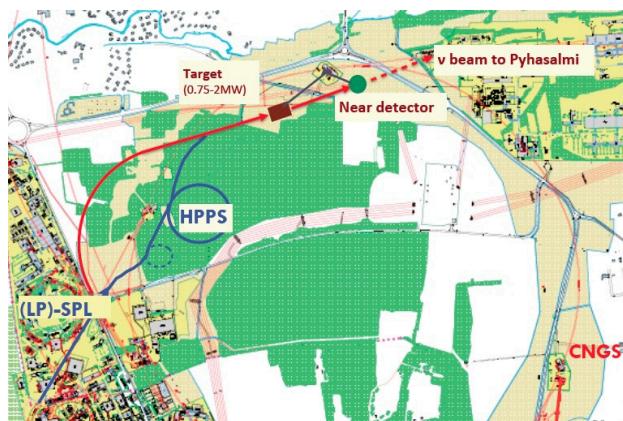


Figure 1: One of the possible layouts for accelerators and beam lines in view of the neutrino beam production to Pyhäsalmi, CN2PY.

LP-SPL AS INJECTOR

The LP-SPL [10] is a low power version of the SPL [11], proposed for the neutrino factory. Both are using LINAC4, presently being constructed at CERN, as front-end.

In summary the LP-SPL provides H^- ions at an energy of 4 GeV and a repetition rate of 2 Hz with about 1.1×10^{14} protons per pulse and a duration of 900 μs . This corresponds to an average beam power out of the LP-SPL of 0.14 MW [12].

LINAC4, once commissioned, will provide beam to the present, but upgraded, proton accelerator chain at a rate of about 1 Hz. Since the LINAC4 LP-SPL chain is foreseen to operate at 2 Hz, the HP-PS will practically receive beam from the LP-SPL at a rate of 1 Hz, corresponding to 50% of the LINAC4 repetition rate and thus imposing an additional constraint to the design of the HP-PS.

HP-PS OPTIONS

Preliminary design parameters for several options of a HP-PS ring have been documented in [13]. The average beam power can be calculated using Eq. 1, where E_K is the kinetic energy of the Beam, N_p is the total number of

protons, F_{rep} is the repetition rate with which the machine extracts the protons and q is the charge of the proton.

$$P = q \cdot f_{rep} \cdot N_p \cdot E_K \quad (1)$$

As mentioned before, the repetition rate is more or less fixed to 1 Hz, The choice for the extraction energy to reach high beam powers motivates the option for a 50 GeV machine, leaving the intensity as main variable in Eq. 1.

From [13] the design parameters of two out of the five rings proposed correspond reasonably well to the constraints and requirements and are summarized in Table 2. The intensity per pulse and the pulse length to be provided by the LP-SPL are beyond the present nominal design values and would need to be addressed. The dipole ramp rates are quite high and a more profound study on the magnet side will be required, considering the option of using super-ferric magnets.

Table 2: Summary of Main Design Parameters of the Two Options that Comply Most with the Constraints and Requirements

| Parameter | HP-PS IV | HP-PS-V |
|---|----------------------------------|-------------------|
| Circumference [m] | 1256 | 1256 |
| Symmetry | 3 / 4-fold | 3 / 4-fold |
| Beam Power [MW] | 2 | 2 |
| Repetition rate [Hz] | 1.3 | 1 |
| Kinetic Energy @ inj/ext. [GeV] | 4/50 | 4/50 |
| Protons/pulse [$\times 10^{14}$] | 1.9 ¹⁾ | 2.5 ¹⁾ |
| LP-SPL pulse length [ms] | 1.6 ¹⁾ | 2 ¹⁾ |
| Dipole ramp rate [T/s] | 4 | 3.1 |
| Bending fields @ inj./extr. [T] | 0.17/1.7 | 0.17/1.7 |
| Fractional beam loss [$\times 10^{-4}$] | 6.5 | 6.5 |
| Space-charge tune-shift H/V | -0.2/-0.2 | -0.2/-0.2 |
| Lattice type | Resonant NMC arc, doublet LSS | |
| Norm. emit H/V [μm] | 10.5/10.3 | 13.7/13.4 |
| Max beta H/V [m] | 60/60 | 60/60 |
| Max. dispersion [m] | 5 | 5 |
| Dipole gap height [mm] | 105 | 120 |
| RMS electrical Power [MW] | 19.3 | 17 |

¹⁾ Values beyond nominal design of the LP-SPL.

PRELIMINARY IDEAS ON RF CHOICES

For the PS2, two different types of RF systems were considered, a wide band 10 MHz system, as presently successfully used in the CERN PS, and a 40 MHz system

[14]. The later was preferred for two reasons: 1) the $n \times 25$ ns bunch spacing requirement of the LHC together with 2) the LP-SPL, which offers a beam chopped at a frequency of up to 40 MHz. For the HP-PS these constraints do not apply, as the chopper can provide a beam chopped at both 10 and 40 MHz.

Table 3. gives an overview of some beam and machine parameters related to the RF system options.

A kicker gap of 2 RF buckets at 10 MHz and 6 at 40 MHz, corresponding to approximately 150 ns has been taken into account for the fast extraction.

Table 3: Some Beam and Machine Parameters related to RF System Options

| Parameter | HP-PS-IV | | HP-PS-V | |
|-----------|-----------------------------|--------|---------|--------|
| | 10 MHz | 40 MHz | 10 MHz | 40 MHz |
| Injection | p [GeV/c] | 4.8 | 4.8 | |
| | Gamma | 4.26 | 4.26 | |
| | Beta | 0.9721 | 0.9721 | |
| | f _{Rev} [kHz] | 231.91 | 231.91 | |
| | Harmonic | 42 | 170 | 42 |
| | N _{Bunches} | 40 | 164 | 40 |
| Ejection | F _{RF} [MHz] | 9.47 | 39.42 | 9.47 |
| | p [GeV/c] | 50.93 | 50.93 | |
| | Gamma | 53.29 | 53.29 | |
| | Beta | 0.9998 | 0.9998 | |
| | f _{Rev} [kHz] | 238.53 | 238.53 | |
| | Harmonic | 42 | 170 | 42 |
| | N _{Bunches} | 40 | 164 | 40 |
| | F _{RF} [MHz] | 10.2 | 40.55 | 10.0 |
| | p/bunch [10 ¹¹] | 47.5 | 11.59 | 62.5 |
| | | | | 15.24 |

A frequency sweep of 3% for the 10 MHz system is presently common practice in the CERN PS. For the 40 MHz system this might require some R&D.

The bunch intensities are very high and more detailed beam dynamics studies are required for both the transverse and longitudinal plane. Further studies also need to address the RF voltage requirements, in particular during the first phase of the acceleration cycle.

SUMMARY

As part of the LAGUNA-LBNO project, conducted within the FP7 framework, CERN is presently studying the feasibility of a 30 - 50 GeV high-power high-energy proton synchrotron, with the LP-SPL as injector, aiming at a beam power on target of 2 MW.

Different high beam power facilities, such as SNS and ISIS, aim at low energies, high intensities and high repetition rates. As soon as higher energies are involved the repetition rate goes down drastically and the beam power is compensated by a combination of high beam

intensity and high energy. The beam energy for the HP-PS is identical to PS2 and the nominal Main Ring at J-PARC, which aims at producing 0.75 MW of beam power. However, the HP-PS aims at more than 2.5 times the J-PARC Main Ring beam power, requiring a higher repetition rate or an increase of beam intensity, but most likely a combination of both. Designing such a machine will be very challenging and many studies will soon have to be initiated in order to address transverse and longitudinal beam dynamics, but also the requirements in terms of RF systems and the feasibility of magnets with a 1.7 T field and a 4T/s ramp rate.

REFERENCES

- [1] LAGUNA-LBNO FP7 design study, Grant agreement no. 284518, July 2011.
- [2] T. Patzak et al., "LAGUNA-LBNO: Large Apparatus studying Grand Unification and Neutrino Astrophysics and Long Baseline Neutrino Oscillations", TAUP 2011, Journal of Physics: Conference series 375 (2012).
- [3] S. Henderson, et al., "Status of the SNS Beam Power Upgrade Project", EPAC 2006, Edinburgh, Scotland, June 2006.
- [4] C.M. Warsop et al., "Status of Injector Upgrade Studies for the ISIS Synchrotron", IPAC2011, San Sebastian, Spain, September 2011.
- [5] J.W.G. Thomason, et al., "Megawatt Upgrades for the ISIS Facility", EPAC08, Genoa, Italy, June 2008.
- [6] "Accelerator Technical Design Report for High-Intensity Protons Accelerator Facility Project, J-PARC", JAERI, KEK Report 2002-13, March 2003.
- [7] T. Koseki, et al., "Status of J-PARC Main Ring Synchrotron", PAC07, Albuquerque, USA, June 2007.
- [8] E. Gschwendtner, et al., "Performance and Operation Experience of the CNGS Facility", IPAC10, Kyoto, Japan, May 2010.
- [9] M. Benedikt, et al., "Design Optimization of PS2", PAC09, Vancouver, Canada, May 2009.
- [10] F. Gerigk et al., "The Low Power SPL" Beam'07, Geneva, Switzerland, October 2007.
- [11] F. Gerigk et al., "Layout and Machine Optimisation for the SPL at CERN", LINAC2012, Tsukuba, Japan, September 2010.
- [12] F. Gerigk, SPL Parameter List, <https://twiki.cern.ch/twiki/bin/view/SPL/SPLparameterList>
- [13] Y. Papaphilippou et al., "Design Parameters of a High-Power Proton Synchrotron for Neutrino Beam at CERN", IPAC'12, New Orleans, USA, May 2012.
- [14] M. Benedikt, S. Hancock, "Analysis of RF Scenarios for the PS2", CERN-AB-Note-2008-028 OP, May 2008.