Back-up Document for
ESSnuSB (European Spallation Source neutrino Super Beam)
to the 2026 update of the European Strategy for Particle Physics

Corresponding authors: Marcos Dracos[1], Tord Ekelöf[2], George Fanourakis[3]
on behalf of the ESSnuSB Collaboration

Abstract

ESSnuSB (the European Spallation Source neutrino Super Beam) is a design study for a Long Baseline (LBL) neutrino experiment to precisely measure the CP violation in the lepton sector, at the second neutrino oscillation maximum, using a beam driven by the uniquely powerful ESS proton linear accelerator in Lund, Sweden, a near detector suite and two large underground water Cherenkov detectors of a total fiducial volume 540,000 m^3, located 360 Km north of Lund. The ESSnuSB Conceptual Design Report showed that after 10 years of running, about 72% of the possible CP-violating phase, δ_{CP}, range will be covered with 5σ C.L. to reject the no-CP-violation hypothesis. The expected precision for δ_{CP} is better than 8° for all δ_{CP} values, making it the most precise proposed experiment in the field. The ESSnuSB collaboration is currently working on the extension project, the ESSnuSB+, which aims in designing two new facilities, a Low Energy nuSTORM and a Low Energy Monitored Neutrino Beam to be used to precisely measure the neutrino-nucleus cross-section in the energy range of 0.2–0.6 GeV. A new water Cherenkov detector will also be designed to measure cross sections and also serve to explore the sterile neutrino case in a Short Baseline (SBL) experiment. An overall status of the project is presented together with the ESSnuSB+ additions.

[1] IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France. email: marcos.dracos@in2p3.fr

[2] Department of Physics and Astronomy, FREIA Division, Uppsala University, P.O. Box 516, 751 20 Uppsala, 33 Sweden. email: Tord.Ekelof@physics.uu.se

[3] Institute of Nuclear and Particle Physics, NCSR Demokritos, Neapoleos 27, 15341 Agia Paraskevi, Greece. email: gfan@inp.demokritos.gr

Answering Questions for projects

ESSnuSB

1. Stages and parameters
a. The main stages of the project and the key scientific goals of each
b. Whether the ordering of stages is fixed or whether there is flexibility
c. For each stage, the main technical parameters
d. The number of independent experimental activities and the number of scientists expected to be engaged in each.
2. Timeline
a. The technically-limited timeline for construction of each stage
b. The anticipated operational (running) time at each stage, and the expected operational duty cycle

ESSnuSB Stages, parameters, timeline

The development and running of the ESSnuSB Research Infrastructure is staged during the construction-Installation and Operation phases as follows:

Stage I: Low energy muon neutrino(antineutrino) cross section with water measurements using the LEMNB (Low Energy Monitored Neutrino Beam). It includes a construction-installation and an operation phase.

The first stage includes the work required to obtain a neutrino (antineutrino) beam via LEMNB facility. It includes the necessary intervention to the ESS linac to provide extra proton pulses of low intensity concurrently with baseline linac operation for spallation neutron production, the construction and installation of the extraction line items, the target and focusing system, the decay pipe, the instrumentation of the decay pipe and the beam dump. This part of the phase will require three years of at least ten scientists.

Stage I also includes the construction and installation of the near-near water Cherenkov detector (named LEMMOND), the preparation of the optical modules, the development of the data acquisition, monitoring and control system, and the installation of LEMMOND. Also, the water purification system with the addition of gadolinium will have to be acquired and installed. These operations will require four years of at least five scientists.

Most of the above items can be worked in parallel.

The operation phase of stage I involves the operation of the LEMNB, the synchronization of the neutrino monitoring system in the decay pipe and the data acquisition with LEMMOND, the collection of events and the data analysis to extract the muon neutrino (antineutrino) cross sections. Data taking has been foreseen for three years and the work will require eight FE scientists.

Stage II. Low energy muon and electron neutrino(antineutrino) cross section with water measurements using the LEnuSTORM (Low Energy neutrinos from Stored Muons) facility and the Short Base Line neutrino oscillation experiment. Stage II also includes a construction-installation and an operation phase.

The second stage includes the necessary modifications of the ESS linac, the construction /installation of the accumulator ring, transfer lines (beam to accumulator, accumulator to target), the target and the focusing/selection system, the beam dump, the transfer line to the muon storage ring and muon storage ring itself. It also includes the adaptation of LEMMOND to run with the LEnuSTORM. This stage also involves work to construct and install the near water Cherenkov detector and its similar to LEMMOND subsystems. These operations will require six years of at least ten scientists, and most of them can be done in parallel.

In the operation phase of the second stage, once the muon storage ring producing muon neutrinos (antineutrinos) and electron antineutrinos (neutrinos) is commissioned, the LEMMOND will be used to collect neutrino-water interaction data for cross-section measurements. In parallel, the ESSnuSB near water Cherenkov detector will be commissioned to form together with LEMMOND a Short Base Line (SBL) neutrino oscillation experiment. Combined data for sterile neutrino searches will be thus taken. These running operations will require six years of twenty scientists.

Stage III. Long Base-Line (LBL) instrumentation and neutrino oscillation experiment. It includes a construction/installation and an operation phase.

In parallel to the previous stages the additional instrumentation and the detector elements as well as the construction of the large far detector needed for the LBL neutrino(antineutrino) running will be in the process of construction/installation. These include the four-fold switch-yard transfer line from the accumulator to the ESSnuSB target station, the four-fold target station and focusing horns, the beam dump, the emulsion neutrino detector, the SFGD detector, the excavation of the hoist shaft, the access tunnels, technical gallerie and caverns in the Zinkgruvan mine, the two far detectors, the water purification systems, and the overall data acquisition, monitoring and control system. These operations will need at least ten years to be completed with the help of about thirty scientists.

The operation phase of the third stage involves the running of the ESSnuSB main LBL experiment, using the full neutrino beam power and involving the collection of neutrino and antineutrino data in all near and far detectors. The operation phase of the third stage includes running for proton decay and astrophysics data and would require at least forty scientists for twenty years.

Between stage II and stage III of the operation phase, a technical stop would be needed to install the additional elements in the target cavern and disconnect the transfer line to the LEnuSTORM ring.

The timeline is summarized below. Our intention is that we shall not interfere in any significant way with the ESS operations for spallation neutron production.

PHASE	FROM-TO (year)	COMMENT
DESIGN	2017-2026	Conceptual design
PREPARATION	2027-2030	preliminary Technical Design
PERMISSION	2030-2033	some 3-4 years to obtain the necessary funding, permissions and environmental studies.
CONSTRUCTION and INSTALLATION	2033-2043	Staged implementation of LEMNB and LEMMOND by 2037, LEnuSTORM by 2039 and LBL ESSnuSB by 2043
OPERATION	2037-2066	Staged operation of LEMNB (three years data-taking), LEnuSTORM (six years data-taking) and LBL ESSnuSB (twenty years data-taking). At the end of the LEnuSTORM operation we need 1-2 years to switch from stage II operation to stage III (LBL) .

3. Resource requirements

a. The capital cost of each stage in 2024 CHF

b. The annual cost of operations of each stage

c. The human resources (in FTE) needed to deliver or operate each stage over its lifetime, expressed as an annual profile

d. Commentary on the basis-of-estimate of the resource requirements

ESSnuSB Resource requirements

A preliminary estimate of the investment cost of ESSnuSB was done for and published 2022 in the arXiv version of the ESSnuSB Conceptual Design Report https://arxiv.org/abs/2206.01208 on page 207, shown below in table I. The final cost estimate will be completed with the CDR of the ESSnuSB+ project.

In this estimate the civil engineering costs on the ESS site were not included. The Low Energy Monitored Neutrino Beam, and the Low Energy nuSTORM muon Storage Ring are infrastructures on the ESS site, the conceptual design of which is being studied in the current ESSnuSB+ Horizon Europe design study to be concluded, including a cost estimate, in 2026. A very preliminary estimate of the costs for ESS site civil engineering and these two additional infrastructures results in a cost of order 600 M€, implying a total ESSnuSB investment cost of ca 2 B€.

As to the ESSnuSB operation costs, no study has been done yet. A rough rule of thumb for the operation costs of a research infrastructure is that it is of the order of 10% of the investment cost, i.e. ca 200 M€ per year in the case of ESSnuSB. The confidence level of this estimate is obviously low.

The requirements for human resources (leading scientists and engineers) were described in the previous section and they are tabulated here below in table II.

Table I. Cost for the LBL experiment of the ESSnuSB RI.

Item	Sub-item	Cost (M€)	Cost (%)
Linac Upgrade	Ion Source and Low-Energy Beam Transport (LEBT)	5.00	0.36%
	Radio-Frequency Quadrupole	6.90	0.50 %
	Medium Energy Beam Transport (MEBT) Upgrade	3.00	0.22%
	Drift-Tube Linac with BPMs, BCMs	13.40	0.97%
	High-Beta Linac (HBL) Upgrade	10.40	0.75%
	33 Modulator Upgrades	3.50	0.25%
	8 New Modulators	9.00	0.65%
	15 Grid-Modulator Transformers	5.60	0.41%
	11 Grid-Modulator Transformers Retrofitted	0.50	0.04%
	26 Solid-State Spoke Amplifiers	26.00	1.88%
	New Klystrons for upgraded HBL	12.10	0.88%
	Remaining Klystron Refurbishment/Replacement	25.20	1.82%
	Cryogenics, Water Cooling, Civil Eng.	12.00	0.87%
	Total	**132.60**	**9.59%**
Accumulator	**Item**	**Cost (M€)**	**Cost (%)**
	DC Magnets and Power Supplies	50.00	3.62%
	Injection system	11.00	0.80%
	Extraction System	7.00	0.51%
	RF Systems	16.00	1.16%
	Collimation	8.00	0.58%
	Beam Instrumentation	19.00	1.37%
	Vacuum System	24.00	1.74%
	Control System	30.00	2.17%
	Total	**165.00**	**11.94%**
Target Station	**Item**	**Cost (M€)**	**Cost (%)**
	Target Station	32.00	2.32%
	Proton Beam Window System	5.20	0.38%
	PSU + Striplines	5.40	0.39%
	Target and Horn Exchange System	40.42	2.92%
	Facility Building Structure	26.60	1.92%
	General System and Services	21.80	1.58%
	Total	**131.42**	**9.51%**
Detectors	**Item**	**Cost (M€)**	**Cost (%)**
	Emulsion Detectors	2.00	0.14%
	Super Fine-Grained Detector	5.49	0.40%
	Near Water Cherenkov Detector	25.22	1.82%
	Far Water Detector	399.35	28.89%
	Underground Cavern Excavations	521.15	37.70%
	Total	**953.21**	**68.93%**
Grand Total		**1382.23**	**100.00%**

Table II. Human resources required for the ESSnuSB RI.

PHASE	STAGE	WORK ITEM (# FTE leading scientists and engineers per item)	Stage total FTE scientists
CONSTRUCTION and INSTALLATION 10 years (2033-2043)	I (6 years)	BEAM (5), LEMNB (5), LEMMOND (5)	15
	II (6 years)	Linac modifications (5), Accumulator-target (5), LEnuSTORM (5) ESSnuSB LBL near detector (5)	20
	III (10 years plus 2 years switch)	ESSnuSB LBL complete near detector complex (8), four target-horn system (4), far detector (8)	20
OPERATION 29 years (2037-2066)	I (3 years)	LEMNB – LEMMOND (10)	10
	II (6 years)	LEnuSTORM (5)– LEMMOND (5) – Near detector complex (10)	20
	III (20 years)	ESSnuSB LBL (40)	40

The current number of members in the collaboration is above 90. We expect that in the stage of construction the collaboration will be expanded and is expected to include of the order of 500 members.

As we do not yet have a Technical Design Report with a final investment cost estimate, we do not have the basis for negotiating financial contributions, in particular their amounts, with the ESSnuSB member-state research funding authorities. Our current baseline assumption is that the member state contributions shall be proportional to their relative Gross National Product (GNP), a scheme used e.g. by CERN. Anyhow, the contributions from the member states can only be the object of negotiations between the member states, which can only start once we have a firm cost estimate by 2030.

4. Environmental impact

a. The peak (MW) and integrated (TWh) energy consumption during operation of each stage
b. The integrated carbon-equivalent energy cost of construction
c. Any other significant expected environmental impacts

The main power consumption during the operations is the power consumed by the linac accelerator of ESS. The total electric power consumption of the ESS 5 MW linac and spallation target will be 400 GWhours/ year. Of this, 200 GWhours/year will be used for cooling at ESS and will be returned in the form of hot water to be used for heating in the city of Lund, resulting in a net consumption of 200 GWhours/year. When increasing the linac power to 10 MW and operating the neutrino production target station for the concurrent production of the long baseline neutrino beam, the net power consumption will increase from 200 to 400 GWhours/year. The operation with the LEMNB and LEnuSTORM will require a smaller amount of power. They all will be estimated during the technical design of the experiment. The carbon-equivalent energy cost of the construction will also be estimated in the technical design.

However, there are environmental benefits to refer to. As mentioned, half the electric power consumption of ESS will be used for cooling and will be reused for heating houses in the city of Lund. This will also be the case for the electric energy consumed by ESSnuSB. Further, at the end of the project the huge deep-underground caverns, where the two far water Cherenkov detectors will be installed, can be used for pumped hydroelectric energy storage. A third benefit involves using the two far water Cherenkov detectors to do muon tomography to reveal dangerous underground voids and valuable ore-rich locations.

5. Technology and delivery

a. The key technologies needed for delivery that are still under development in 2024, and the targeted performance parameters of each development

b. The critical path for technology development or design

c. A concise assessment of the key technical risks to the delivery of the project

d. An estimate of financial and human resources needed for R&D on key technologies

The ESSnuSB project relies on existing technologies which continue to evolve resulting in a more efficient facility by the time the ESSnuSB construction phase begins. As an example, the companies developing optical sensors are already offering better quantum efficiency devices compared to the one available at the time the project design started.

The modifications of the ESS linac have been studied in detail during the first design phase (2018-2021) and the construction of two novel facilities for high quality neutrino beams i.e. the Low Energy Monitored Neutrino Beam and the Low Energy neutrinos from Stored Muons are being designed in the current phase of the design (ESSnuSB+). There is work going on to test the current design of the target and verify the simulations that this design can handle the power of the beam.

The technical development of the proposed neutrino research infrastructure will impact other fields that plan to use very high intensity proton accelerators like Accelerator Driven Systems (ADS) and hadron therapy. Among the technical developments that will have such effects are that of the high current, long pulse H- ion source and of the target required to stand the impact of very short pulses of very high power. The development of the 500 000 m^3 underground Water Cherenkov detector equipped with an order of 100 000 high-resolution photon detectors will impact the photon-detector industry and modern rock engineering technology. It is expected that the industrial companies that will be contacted to investigate the feasibility of the industrial production of ESSνSB components will see an economic and technical interest in engaging with the project. It is also expected that the realization of the proposed project will improve societal conditions by its technological developments that will lead to a greener and safer world. Essentially all technology developments will require collaboration with industry, both in the design and development phase and in the production phase. The high requirements that our project will place on its different components will require us to follow the development work in industry. One example of this is the case of photodetectors. The about. 20,000 50cm diameter photomultipliers that have recently been ordered from Hamamatsu for the Hyper-K experiment in Japan, saturated the company's production line capacity for several years. At this moment there are no further orders for that production line, and it is not clear whether the production line could be maintained till ESSnuSB places its order for photodetectors. This is a possible risk for the project, on the other hand, there are several new photodetector types that have been developed meanwhile providing higher time and spatial resolution, like e.g. the Large Area Picosecond Photodetectors (LAPPD) just to mention one example. Currently the LAPPDs can be produced in small series by a US firm but not yet in the quantities and sizes required for ESSnuSB. We are following also other developments and hope to have by the time when we will have to place the order that an even more performing type of photodetectors will be available for production. Another example is the development of new rock engineering methods for the excavation and stabilization of the large Far Detector underground caverns. The two ESSnuSB underground caverns will be the largest in the world (270 000 m^3 each) and must be designed for the specific rock available near the Zinkgruvan mine. There are firms specialized in this technology for which the design of the ESSnjuSB caverns will be an outstanding challenge and which will have several possible other applications in the future.

6. Dependencies

a. Whether a specific host site is foreseen, or whether options are available

b. The dependencies on existing or required infrastructure

c. The technical effects of project execution on the operations of existing infrastructures at the host site

The ESSnuSB Research Infrastructure is based on the ESS site in Lund. It relies on a well-studied and documented modification of the existing ESS linac and the use of part of ESS land to install the new facilities, the detectors and the support buildings. The way the 5 MW beam for neutrino generation will be produced by doubling the number of linac pulses from 14 to 28 per second will in no significant way influence or reduce the production of the 5 MW beam for spallation neutron production. The intervention on the current design of the ESS linac will increase the value of ESS as a unique high intensity neutron and neutrino facility in the world. The addition of the two new facilities, LEMNB and LEnuSTORM will revolutionize the neutrino domain by expanding our knowledge on the neutrino-matter interactions and by the potential discovery of sterile neutrinos. LEnuSTORM will contribute to the development of muon colliders. The LBL facility will make advances in the water Cherenkov detection technique and measure the CP violating angle with enough precision so as to allow for the choice of the correct leptogenesis model explaining the reason for the lack of antimatter in the universe.

7. Commentary on current project status

a. A concise description of the current design / R&D / simulation activities leading to the project, and the community pursuing these

b. A statement of any major in-kind deliverables already negotiated

c. Any other key technical information points in addition to those captured above, including references to additional public documents addressing the points above.

In 2017 the ESSnuSB consortium received 3 MEUR funding from the H2020 program to finance a Design Study of the ESSνSB project of a total cost of 4.7 M€, during the period 2018-2021[4]. The 15 member Institutes of the ESSνSB H2020 INFRADEV-1 Design Study were: Centre National de la Recherche Scientifique (**CNRS**) France (two laboratories), Uppsala University (**UU**) Sweden, Royal Institute of Technology (**KTH**) Stockholm Sweden, European Spallation Source (**ESS**), Cukurova University Adana (**CU**) Turkey, Universidad Autónoma de Madrid (**UAM**) Spain, University of Hamburg (**UHH**), Demokritos Center

[4] http://essnusb.eu/

(**NCSR)** Athens Greece, Istituto Nazionale di Fisica Nucleare (**INFN)** Italy (two laboratories), Rudjer Boskovic Institute (**RBI)** Croatia, Sofia University St. Kliment Ohridski (**UniSofia)** Bulgaria, Lund University **(LU)** Sweden, University of Science and Technology (**AGH)** Krakow Poland, European Organisation for Nuclear Research (**CERN)**, University of Geneva (**UniGe)** Switzerland and University of Durham (**UDUR)** UK.

In 2022 the ESSvSB consortium received 3 MEUR funding from the Horizon program to further the Design Study of the ESSvSB project, called ESSnuSB+, of a total cost of 5.0 M€, during the period 2023-2026 [see footnote 1]. The 20 member Institutes of the ESSvSB Horizon INFRADEV-1 second Design Study are: Centre National de la Recherche Scientifique (**CNRS)** France (two laboratories), Uppsala University (**UU)** Sweden, Royal Institute of Technology (**KTH)** Stockholm Sweden, European Spallation Source (**ESS)**, Cukurova University Adana (**CU)** Turkey, Demokritos Center (**NCSR)** Athens Greece, Istituto Nazionale di Fisica Nucleare (**INFN)** Italy, Rudjer Boskovic Institute (**RBI)** Croatia, Sofia University St. Kliment Ohridski (**UniSofia)** Bulgaria, Lund University **(LU)** Sweden, University of Science and Technology (**AGH)** Krakow Poland, European Organisation for Nuclear Research (**CERN)**, Université de Strasbourg (**UNISTRA**) France, University of Hamburg (**UHH**), Tokai National Higher Education and Research System, National University Corporation (**NU**) Japan, Aristotelio Panepistimio Thessalonikis (**AUTH**) Greece, Lulea Tekniska Universitet (**LTU**) Sweden, Università degli studi Roma Tre (**UNIROMA3**) Italy, Università degli studi di Milano-Bicocca (**UNIMIB**) Italy, Università degli studi di Padova (**UNIPD**) Italy, and Consorcio para la construcción, equipamiento y exploracion de la sede española de la fuente Europea de neutrones por espalación (**ESSB**) Spain. The ESSvSB and ESSnuSB+ Design Studies are coordinated by CNRS and the consortium numbers over 90 physicists, from 28 Institutions in 14 counties.

The current activities involve the design of the Low Energy Monitored Neutrino Beam, the design of the Low Energy neutrinos from Stored Muons facility, the design of the near-near water Cherenkov neutrino detector LEMMOND, the improvement of the analysis software of the LBL experiment and the study of more physics cases expanding the Physics potential of ESSnuSB such as astroparticle physics, proton decay, the sterile neutrinos case and other beyond the Standard model physics.

The plan is that the ESSvSB INFRADEV-1 Design Studies 2018-2021 and 2023-2026 will be followed by an INFRADEV-2 Preparatory Phase 2027-2030 resulting in a preliminary Technical Design Report, including an updated cost estimate. From 2030, this Report will be used as a basis to obtain permits and for seeking financial support from European governments to enable the start of ESSvSB construction work around 2033. By that time the ESS baseline infrastructure with the proton linac, the neutron spallation target and 15 neutron instruments will already have been built up and started operation. It is foreseen that the build-up of the neutrino production infrastructure at ESS and the neutrino detector will be going on for ca. 7 years leading up to the start of data taking around 2040. A first task for ESSvSB, after the neutrino cross section measurement campaigns will be to discover leptonic CP violation and measure δ_{CP} with high precision. In subsequent updates and according to the physics needs, this neutrino Super Beam could be transformed to a muon facility to serve a Neutrino Factory or/and a muon collider.