Letter of Interest to Snowmass 2021

The ESS neutrino Super Beam Design Study (ESSnuSB) and the High Intensity Frontier Initiative (HIFI)

The linear accelerator of the European Spallation Source, ESS, in Lund, Sweden with its 5 MW proton beam power will soon be the world's most powerful accelerator. Moreover, its duty-cycle at 5 MW will be only 4%, which leaves room for increasing the beam power and duty cycle to 10 MW and 8%, respectively, requiring an additional investment that is relatively modest compared with the already committed 600 MEUR for the basic ESS accelerator.

ESS is currently under construction and roughly 70% complete; first science will start in 2023 and full accelerator power should be reached around 2026. The opportunity to add to the capabilities represents an outstanding opportunity not only for Spallation Neutron Science - for which the originally foreseen 5 MW will make ESS the world's most capable facility - but also to establish a new and world-leading programme of Intensity Frontier Particle Physics - which the increased duty cycle would make possible.

A crucial addition required for the realization of the full potential of this ESS accelerator power upgrade is that of a roughly 400 m circumference accumulator ring to be used to compress the duration of each accelerator pulse from ca 3 milliseconds to about 1 microsecond. Such a pulse-compressor ring, which is already being designed within the EU supported ESSnuSB neutrino Super Beam project for ESS, can also be used to benefit other intensity frontier projects.

European Spallation Source neutrino Super Beam (ESSnuSB)

The high power of the ESS linac offers the possibility to create a uniquely intense second-generation neutrino Super Beam. This will allow sufficient statistics to be provided for measuring leptonic CP violation with a megaton water Cherenkov detector placed at the **second neutrino oscillation maximum**, where the CP-violating term in the neutrino oscillation probability, proportional to L/E, is significantly larger, by a factor 3 at the oscillation peak value, as compared to the first oscillation maximum. This is of high importance as the accuracy in neutrino-beam measurements is notoriously limited by the systematic, rather than statistical, errors. These systematic errors are primarily due to the lack of precise experimental neutrino-nucleus cross-sections data and to basic uncertainties in the nuclear-physics models of neutrino-nucleus interactions, two research areas where progress has been and is still very slow.

Currently, the systematic error in the signal is, after a decade of running, estimated to be ca 6% in the T2K experiment in Japan, which has its detector located at the first oscillation maximum. Measuring the CP angle δ_{CP} at the second oscillation maximum with the same systematic error of ca 6% would thus correspond to measuring it at the first maximum with much smaller systematic errors, which will clearly be very challenging to achieve. With systematic errors similar to those of the current T2K, CP-violation can be discovered at 5σ confidence level in 62%/70% of the range of δ_{CP} values after 10/20 years of data taking at a distance between ESS and the far detector site of 540 km (the ESSnuSB Garpenberg far-detector site option). The precision in the measurement of the δ_{CP} will depend on the value of δ_{CP} and the choice between two possible ESSnuSB baselines. As an example, the standard error in δ_{CP} would after 10 years of data taking be 13° for δ_{CP} = -90° (i.e. for maximal CP violation) with a baseline of 360 km (the ESSnuSB Zinkgruvan far-detector site option) and 6° for δ_{CP} = 0° (i.e. close to CP conservation) with a baseline of 540 km.

The Design Study of the ESSnuSB project (https://essnusb.eu/), supported by the European Union Research Directorate, is under way since January 2018, with the participation of 17 research groups in 11 European countries and will result in a Conceptual Design Report in December 2021. An ESSnuSB mid-term report is available at https://essnusb.eu/DocDB/0007/000706/002/ESSnuSB_2019_report.pdf from which the performance figures above are quoted. In this document are also reported the current achievements of the five ESSnuSB Working Groups on, respectively, the Linac power upgrade, the Accumulator ring, the neutrino production Target Station, the two neutrino Detectors - one monitoring near-detector located on the ESS site and one megaton water-Cherenkov far-detector located near the second neutrino oscillation maximum - and the Physics simulation and performance analysis.

High Intensity Frontier Initiative (HIFI)

An open workshop "Prospects for Intensity Frontier Physics with Compressed Pulses from the ESS Linac" was organized at Uppsala University, Sweden 2-3 March 2020. This workshop was set up to explore the wider use of the ESS linac power upgrade and of the accumulator ring, both already under design study by the ESSnuSB consortium and, most significantly, the fact that, concurrently with the neutrinos, a copious number of muons (>10^{21}/year) will be produced. These muons can be used to realize a broad High Intensity Frontier Physics program with nuSTORM for neutrino cross-section measurements and sterile neutrino searches, with a Neutrino Factory for precision PMNS parameter measurements and with the studies of muon 6D cooling for a Muon Collider as a Higgs Factory. The Accumulator ring can be used as the first stage of the proton beam compression for the Neutrino Factory and for the Muon Collider. The high proton power and the 1.3 µs pulses will furthermore allow for Decay at Rest (DAR) experiments and Coherent Neutrino Scattering experiments with very small random background. The accumulator ring can also be used, employing slow extraction, to produce beam pulses of intermediate length, like 50 microseconds, which will be of fundamental interest for certain important types of Spallation Neutron Science, thus significantly widening ESS's already world-unique capacity as a neutron spallation source.

The following presentations were given of the projects that will be made highly competitive by the use of the high power of the upgraded ESS linac and of the pulse compression provided by the ESSnuSB accumulator ring:

- Carlo Rubbia: The use of the ESS linac to create a Muon Collider
- Marcos Dracos: The ESS neutrino Super Beam Design Study
- Ken Andersson: Short Pulses for Neutron Physics at ESS
- Sam Tygier: The prospects for nuSTORM at ESS
- Jaroslaw Pasternak: The prospects for an ESS based Neutrino Factory
- Adrien Hourlier: The possibilities of Decay-at-Rest experiments at ESS
- Juan Collar Colmenero: Opportunities for Coherent Neutrino Scattering at the ESS

The main conclusion of the workshop was that all proposed projects would significantly profit from the high power of the ESS linac and from the compression of the linac pulses provided by the ESSnuSB accumulator ring. At this level, no 'show-stoppers' have been identified for any of the above projects. It was however made clear that a significant amount of design study work would be needed for each of the projects to demonstrate their feasibility and cost. The workshop programme and the slides of the presentations are available at https://indico.cern.ch/event/849674/.

The workshop was concluded with the forming of a working group of contact persons to work out a common design study program named "High Intensity Frontier Initiative" (HIFI) for the projects proposed at the workshop, to be used as a basis for applications to the various relevant funding schemes of the European Union's Horizon Europe program, that will be published in the beginning of 2021.

Collaboration

The interested community active in the ESSnuSB design study and HIFI initiative is composed of more than 70 physicists affiliated to the following institutions:

Centre National de la Recherche Scientific at IPHC (Strasbourg) and at IJCLab (Orsay), France
Cukurova University, Adana**,** Turkey
Demokritos Center, Athens, Greece
Donostia International Physics Center, San Sebastian, Spain
European Organisation for Nuclear Research, Geneva, Switzerland
European Spallation Source, Lund, Sweden
Gran Sasso Science Institute, L'Aquila, Italy
Imperial College, London, UK
Institute of High Energy Physics, Beijing, China
Istituto Nazionale di Fisica Nucleare (INFN) at Bari, at Milano and at Padova, Italy
Lund University**,** Sweden
Massachusetts Institute of Technology, USA
University of Michigan, USA
Royal Institute of Technology**,** Stockholm, Sweden,
Rudjer Boskovic Institute, Zagreb**,** Croatia
Sofia University St. Kliment Ohridski, Sofia, Bulgaria
Universidad Autonoma de Madrid**,** Spain
University of Durham, UK
University of Hamburg, Germany
University of Science and Technology, Krakow, Poland
University of Oslo, Norway
University of Texas, Arlington, USA
University of Thessaloniki, Greece
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References

1. *Report on the results obtained during the second year at midterm of the ESSnuSB Feasibility Study for Employing the Uniquely Powerful ESS Linear Accelerator to generate an Intense Neutrino Beam for Leptonic CP Violation Discovery and Measurements*; The ESSnuSB Collaboration; https://essnusb.eu/DocDB/0007/000706/002/ESSnuSB_2019_report.pdf

2. *The European Spallation Source Neutrino Super Beam Design Study;* M. Dracos and al; Proc. 10thParticle Accelerator Conf. IPAC'19, Melbourne, Australia 19 May 2019.DOI: 10.18429/JACoW-IPAC2019-MOPRB004

3. *Physics Potential of ESSνSB*; M. Blennow, E. Fernandez-Martinez, T Ota, S. Rosauro-Alcaraz; Published in the European Physical Journal C. DOI: 10.11 40/epjc/s10052-020-7761-9

4. *Status of ESS Linac Upgrade Studies for ESSνSB*; B. Gålnander, M. Eshraqi, C. Martins, R. Miyamoto, A. Farricker and M. Collins; Proceedings of IPAC 2019; DOI: 10.18429/JACoW-IPAC2019-MOPTS082

5. *The accumulator ring for the ESSvSB project - a progress report*; Ye Zou; Submitted to Proceedings of the 21st International Workshop on Neutrinos from Accelerators (NUFACT2019).

6. *ESSvSB Target and Horn Studies and Future Development*; E. Baussan; Proc 20th International Workshop on Neutrinos (Nufact2018), 12-18 August, Blacksburg, Virginia.(published in 2019)DOI: 10.22323/1.341.0

7. *Further searches of the Higgs scalar sector at the ESS*; Carlo Rubbia; https://arxiv.org/abs/1908.05664.

8. *A Proposal for a Next Generation European Neutron Source*; K.H. Andersen and C.J. Carlile; Journal of Physics: Conference Series, Volume 746, VI European Conference on Neutron Scattering (ECNS2015) 30 August to 4 September 2015, Zaragoza, Spain

9. *Neutrino Factory*, Dec 2014; M. Bogomilov et al.; Published in Phys. Rev. ST Accel. Beams 17 (2014) no.12, 121002; FERMILAB-PUB-14-555-AD-APC; DOI: 10.1103/PhysRevSTAB.17.121002.

10. nuSTORM - Neutrinos from STORed Muons: D. Adey et al.; Proposal to the Fermilab PAC, (Jul 31, 2013); e-Print: 1308.6822 [physics.acc-ph].

11. *Coherent Elastic Neutrino-Nucleus Scattering at the European Spallation Source*; D. Baxter, J.I. Collar, P. Coloma, C.E. Dahl, I. Esteban et al; JHEP 02 (2020) 123; 1911.00762 [physics.ins-det]; FERMILAB-PUB-19-612-V

12. *A Sterile Neutrino Search with Kaon Decay-at-rest*; J. Spitz; Phys. Rev. D 85 (2012) 093020; arXiv:1203.6050 [hep-ph]

13. *Decisive disappearance search at high Δm^2 with monoenergetic muon neutrinos*; S. Axani, G. Collin, J. Conrad, M. Shaevitz, J. Spitz and T. Wongjirad; Phys. Rev. D 92, no.9, (2015) 092010; arXiv:1506.05811 [physics.ins-det]