Proposal for a lepton CP violation discovery experiment using a neutrino Super Beam from ESS
The ESS proton linac

- European Neutron Spallation Source will be built in Lund using a 2.5 GeV 5 MW superconduction linac to produce

$$10^{23}$$ protons on target/year

i.e. two orders of magnitude more than other accelerators

- Finance volume: ~1 800 Meuro

- 3 y design + 4 y construction, First beams ~2019

- Uppsala University has taken responsibility for the development of the 352 MHz radio-frequency distribution system of the ESS - project
- Project cost 178 MSEK financed by KAW 40 MSEK, Swedish Government 50 MSEK, ESS AB 60 MSEK, VR 13 MSEK and UU 15 MSEK
- Contract signed by UU and ESS managements 10 June 2011 and delegated to the Uppsala Dept of Physics and Astronomy (IFA)
- FREIA Sub-Department in IFA created in September 2011, Board Members: T. Ekelöf (föreståndare), R. Ruber (projektledare), A. Rydberg (RF), V. Ziemann (v. projektledare)
Consequences of the large value of $\sin^2 2\theta_{13}$ for CP violation measurements

$$P_{\nu_\mu \rightarrow \nu_e} \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 \Delta(1-A)}{(1-A)^2} + \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2 A\Delta}{A^2}$$

$$+ \alpha J \cos(\Delta \pm \delta_{CP}) \frac{\sin \Delta A \sin \Delta(1-A)}{A} \frac{1}{1-A}, \text{ with } \Delta \equiv \frac{\Delta m^2_{31}L}{4E}, \quad A \equiv \frac{2EV}{\Delta m^2_{31}}, \quad \alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

The observation of the CP violating signal requires the interference term in the neutrino oscillation probability, i.e. the third term in the formula, to be of measurable magnitude. The first term is suppressed by $\theta_{13}$ while the second one is suppressed by $L/E$. In order to maximize the interference term and thus the CP violation signal, these two terms should be of similar magnitude. Thus, to compensate for the comparatively large value of $\theta_{13}$ recently discovered, $L/E$ needs to be increased. This is obtained by placing the detector at the second oscillation maximum rather than, as in earlier optimizations, at the first.
Most of the so far existing proposals were made under the assumption of a very small $\theta_{13}$, for which the signal/background ratio was the main limiting factor. For large $\theta_{13}$ this paradigm is shifted to a situation where an accurate control of systematic errors becomes important.

Having a broad neutrino energy distribution allows for an oscillation curve shape analysis rather than just a counting experiment analysis. This implies that the neutrino beam should not be titled with respect to the proton beam.
The MEMPHYS Detector
(studied so far within the FP7 LAGUNA project)

A “Hyperkamiokande” detector to study

• Neutrinos from accelerators (Super Beam)

but also

• Supernovae (burst + "relics")
• Solar neutrinos
• Atmospheric neutrino
• Geoneutrinos
• Proton decay up to ~35 years life time

Water Cerenkov Detector with total fiducial mass: 440 kt:
• 3 Cylindrical modules 65x65 m
• Readout: 3x81k 12” PMTs, 30% geom. cover.
• Order of magnitude cost : 700 MEuro

(arXiv: hep-ex/0607026)
Requirements for the ESS Super Beam experiment

The large volume 440’000 m$^2$ of MEMPHYS, an order of magnitude larger than current neutrino detectors experiments, is needed to obtain a sufficiently large target volume for the detection of the low flux of electron neutrinos. This makes the detector very sensitive to background from cosmic rays which requires that

1. the detector be shielded underground by at least 1000 m of rock

2. the neutrino pulses be made as short as possible (duty cycle $\sim 10^{-5}$)

The first condition means that the detector has to be built deep underground and the second the neutrino beam must have few and very short pulses.
Depth and distance from ESS/ Lund of different mines in Scandinavia

E≈300 MeV
Δm^2_{sun}=7.7x10^{-5} eV^2
Δm^2_{atm}=2.4x10^{-3} eV^2
θ_{23}=45°
θ_{13}=10°
δ_{CP}=0
Garpenberg Mine
Distance from ESS Lund 540 km

Depth 1232 m
Truck access tunnels
Two ore hoist shafts

A new ore hoist shaft is planned to be ready in 3 years, leaving the two ex shafts existing free for other uses
Which is the potential of the ESS linac as a proton driver for a neutrino Super Beam?

The Compressor Ring

The current design of the ESS proton linac will accelerate 3 ms long 50 mA proton pulses to 2.5 GeV at 14 Hz, i.e. It will have a duty cycle of $14 \times 0.003 = 0.042$ which is 2000 larger than required, i.e. the proton pulse length has to be compressed by a factor 2000 to 1.5 μs. This compression can be achieved using a compressor ring in which the whole 3 ms long pulse is accumulated by multi(2000)-turn injection and then ejected in one turn. To obtain a 1.5 μs pulse the ring should have a 450 m circumference.
H⁻ acceleration and injection

Each pulse from the ESS Linac will contain about $10^{15}$ protons. During the 3 ms injection period such a large stored negative charge will repel the successively arriving negatively charged protons. The only chance to be able to accumulate such a charge in a storage ring is to inject H⁻ ions and use a laser to strip off the electrons from the H⁻ ions at the moment when they enter the stored beam.

This implies that the ESS linac must be made to accelerate also H⁻ ions. Since the time for operation of proton acceleration for spallation neutrons must not be reduced this H⁻ acceleration must be simultaneous with proton acceleration.

The proposed plan for simultaneous H⁻ acceleration is to have one 3 ms long 50 mA H⁻ pulse accelerated in the 70 ms long gap between two proton (H⁺) pulses, requiring the linac pulse frequency of 14 Hz to be raised to 28 Hz.
Doubling of the average RF power

For the simultaneous acceleration of 14 proton pulses and 14 H- pulses per second the average power of the linac will have to be doubled from 5 MW to 10 MW, requiring a corresponding doubling of the output power from the linac RF sources.

The cost for this doubling will be a dominant cost for the linac modification project. If the power upgrade can be carried out already during the initial build-up of the linac, modulators, amplifiers and power transfer equipment should be designed for the doubled average power of the linac.
RF power source tests

A prototype 352 MHz spoke cavity for the ESS linac will be tested in the FREIA Laboratory at Uppsala University already as from July 2014 in a cryostat at 14 Hz pulse frequency and at the full instantaneous power required for ESS proton acceleration, which is 350 kW. The 352 MHz power source will be a tetrode. As part of the EUROSB project, the power supplied to the tetrode would be doubled and the pulse frequency raised to 28 Hz, thus doubling the average power to the cavity. The influence of this higher power on the operation of the cavity and on the capacity to cool the cavity itself and, in particular, its RF coupler will be studied.
The space charge problem in the compressor ring

Another problem with the enormous amount of protons stored at comparatively low energy in the compressor ring is the space charge which leads to a defocusing of the stored beam. For a charge of $10^{15}$ protons stored for 3 ms in 450 m circumference storage ring, this defocusing effect is on the limit of being unmanageable. A way to alleviate this problem is to divide the stored charge on four compressor rings, thereby reducing the defocusing effect by a factor 4. This is a trick already used for the CERN PS Booster ring.
Shorter pulses also needed for the ESS neutron application

It is of significant interest to note that spallation neutron users of the ESS have expressed a keen interest in having shorter neutron pulses than 3 ms. For neutrons the optimal pulse length would be of the order of 100 µs.

It would not be possible for economical reasons to have an accumulator ring with a circumference large enough (of order 30 km) to produce such pulses by single turn extraction.

However, with the system of 4 rings each of ca 450 m circumference pulses of about 100 µs length can be obtained by multi-turn extraction.

This option has already been discussed within the ESS and the synergy between the two uses opens the perspective of sharing the investment and operation costs for the H⁻ beam and the accumulator with the spallation neutron users.
The Target

A challenging part of this project is the target to be hit by the 5 MW proton beam to produce the pions needed for the neutrino beam production. Classical monolithic solid targets are almost impossible for this application because of the absence of efficient cooling.

One design which is under investigation is a packed bed of titanium spheres cooled with cold helium gas. Questions have been raised whether the pulsed beam may generate vibrations in the spheres, which could be transmitted to the packed bed container and beam windows and cause degradation of the spheres where they are in contact with each other.

Tests of such a target are planned using the HiRadMat high intensity proton irradiation facility at CERN.
The Neutrino Horn

A key element for generating a neutrino beam is the hadron collector, also called neutrino horn, used to focus in the forward direction the charged pions produced in the proton-target collisions.

The high ESS pulse rate of 14 Hz, 3 times higher than in current projects, and the very high power of the ESS proton beam, 10 times higher than what present proton drivers are providing, also represent a considerable challenge. These conditions could significantly reduce the system lifetime requiring particular studies and tests to be performed.

As a pulsed power supply that is able to provide the very high current (~350 kA) to be circulated inside the horn at the required pulse rate has not been produced so far, such a supply needs to be prototyped.
Which is the optimal base line for the ESS SuperBeam for CP violation discovery?

An important parameter to be determined in EUROSB is the optimal neutrino beam baseline length, determining the choice of the mine where to install the detector. Below is plotted the potential for CP violation and neutrino mass hierarchy discoveries with EUROSB, measured as the fraction of the full CP violation angular range within which CP violation and neutrino mass hierarchy can be discovered, versus the baseline length.

The fraction of the full $\delta$ range $0^\circ - 360^\circ$ within which CP violation can be discovered as function of the baseline length in km for different proton linac energies – for ESS 2.5 GeV. The lower (upper) curves are for CP violation discovery at 5$\sigma$ (3$\sigma$) significance. (Enrique Fernandez)
ESS SuperBeam Physics Performance - CP Violation

The simulation software developed by the EUROnu project has been used to make first evaluations of the potential for CP violation and neutrino mass hierarchy discoveries with EUROSB. The figure below shows the physics performance of ESS SB as compared to other proposals in terms of the $\chi^2$ for CP violation discovery as function of the fraction of the full $\delta$ range $0^\circ$–$360^\circ$ within which CP violation can be discovered.

CP violation performance versus the fraction of $\delta_{CP}$.

LENF, SPL2, ESS, C2Py2, C2Py1, T2HK and LBNE stand for

Low Energy Neutrino Factory (2000 km, 100 kt MIND),
SPL to Canfranc (650 km, 500 kt WC),
ESS Super Beam (400 km, 500 kt WC),
CERN to Pyhäsalmi (SPS, 2300 km, 20 kt resp. 200 kt LAr),
T2HK Japan project and
LBNE USA long baseline, respectively.

(Enrique Fernandez)
Physics Performance for Future SB projects

\[ \delta_{CP} \] resolution versus the \( \delta_{CP} \) angle.

(Enrique Fernandez)
Selection of the mine where to install MEMPHYS

A preliminary study of the geological parameters and existing mining infrastructures will be made of the few mines located within the range 200-550 km from the ESS site. Once the optimal baseline length has been obtained from the improved calculations, the final choice among these mines can be made on the basis of the optimal baseline length, the geological parameters and the existing mining infrastructures.

The selected mine will then be studied in detail collecting geological and rock mechanics information by making core drillings, core logging, rock strength testing and rock stress measurements of the surrounding rock at 1000 m depth in different directions and 500 m distance from active mining activities.

Once a suitable location for the neutrino detector underground halls, which should have a total volume of 600’000 m³, has been determined, a design of the geometry and construction methods for the underground halls will be made based on the measured strength and stress parameters of the rock.
Estimates of investment costs

The price of a CERN-SPL based Super Beam has been estimated to be of the order of **1 000 MEUR** (650 MEUR for the SPL, 200 MEUR for the accumulator and 200 MEUR for the target station).

A principal goal of the EUROSB project is to demonstrate that the ESS linac can also be used to produce a SB. If so, about 550 MEUR can be saved, compared to the cost of the SPL-SB project, assuming that about 100 MEUR will be needed for the ESS linac modifications to produce a SB beam. Furthermore, if the accumulator is built in common with the ESS neutron community, its cost 200 MEUR could be shared with the neutron users community.

The total estimated cost for a ESS neutrino beam is of order **400 MEUR**, to be compared to the order 1000 MEUR required to build such a beam from scratch.

The price of the MEMPHYS neutrino detector has been estimated in the LAGUNA project to be around **700 MEUR**.
EUROSB Feasibility Study

Two PI teams have applied together with several Partners and Associates for a EU Synergy project

The **CNRS Strasbourg PI team** will, in view of their participation in the EUROnu Super Beam Design Study, be oriented principally towards the target/horn station and the **Super Beam optimizations**. The CNRS PI has as Partners the **University of Madrid** and the **UK-STFC** which will contribute with their expertise in neutrino phenomenology and physics performance simulations (Madrid) and in proton target technology (UK-STFC).

The **Uppsala PI team** will, in view of its involvement in the ESS proton linac, be oriented principally towards the **proton linac** and towards the investigation of possible **detector sites** and the surveillance of the **design study of the detector underground hall**. The Uppsala PI team has two partners, **ESS** with its detailed knowledge of, and management responsibilities for, the ESS linac and **CERN** with its experience of developing the SPL proton linac project and an accumulator for a neutrino beam to the Fréjus site. **Stockholm KTH** is participating in the project as an Associate in the project.
CONCLUSION

The EUROSB project proposes to study the utilisation of the ESS proton linac to build a physics competitive and cost effective neutrino Super Beam facility.

The technical feasibility of this project will be studied in detail with the help of computer simulations and prototype tests.

The strong synergy between the use of the ESS linac for spallation neutron production and the proposed, simultaneous use for neutrino beam production presents a unique possibility in Europe to play a significant role on the world level in neutrino physics, in particular in the search for neutrino CP violation.

A discovery of CP violation in the leptonic sector will have strong cosmological implications opening new possibilities to comprehend the matter/anti-matter asymmetry in Universe. Preliminary studies give very promising results compared to other neutrino facility proposals in Europe and elsewhere in the world.
Back-up slides
Metrics of ESS SB for Snowmass

• Science goals
  • discovery potential: yes, unique potential for CPV, potential for MH together with several other experiments
  • physics topics and parameter sensitivity: CPV and $\delta_{CP}$
  • is science unique? yes, the uniquely high ESS proton driver flux ($10^{23}$ protons/year) provides uniquely high CPV sensitivity
  • are there other competing experiments? yes, T2HK (with lower proton flux) and NF (with significantly longer time schedule)
  • complementarity with other experiments? yes, ESS SB has lower neutrino energy 200-500 MeV and shorter base line ca 500 km

• R&D requirements
  • ready for proposal or construction: conceptual proposal 2013, proposal 2015, start of construction 2016
  • limited R&D sufficient (1-2 years): yes, for the detector
  • long-term R&D required (> 2 years): yes, for the neutrino beam
  • synergies with other experiments? yes, with the ESS spallation-neutron scientific program (linac and accumulator in common)

• Cost categories (indicate separately categories for US contribution and total project cost, no precise estimates needed)
  • < $5M ($) - minor construction (below threshold for project reporting)
  • < $50M ($) - e.g. Daya Bay-like, less than LBNE underground option
  • $50-300M ($$$) - e.g. NOvA, mu2e, IceCube-size
  • > $300M ($$$) - e.g. LBNE-I
  • > $1B ($$$$$) - e.g. LBNE-II, NuFact, beta beams: costs of order $300M for ESS linac upgrade and accumulator to be shared with the neutron users, of order $200M for the target and of order $700M for the detector - any US contribution would be most welcome

• Synergies
  • with other experiments? yes, with LNBO, LBNE, T2HK, PINGU
  • with other fields and frontiers? yes, with astroparticle physics, proton life time, geophysics

• US collaborations and leadership
  • US leadership? no
  • US based experiment/facility? no
  • opportunity for international engagement? yes, enlarged international engagement most welcome and needed
  • continued international collaboration? no, but building on earlier experience made in EUROnu, LAGUNA and others

• Timeline and projected schedule: tied to the ESS schedule - ESS is already approved and construction is starting this year
  • R&D timeline: 2013-2016
  • construction time: 2016-2023
  • data taking and science program duration: 2023-2033 (may be continued beyond 2033 with further scientific programs)
Mass hierarchy determination for different base lines

The significance in mass hierarchy determination as function of $\delta_{CP}$ for different base line lengths

(Enrique Fernandez)

Measurements with atmospheric neutrinos will further improve this performance
The Neutrino Mass Hierarchy

The figure below shows the physics performance of ESS SB as compared to other proposals in terms of the $\chi^2$ for Neutrino Mass hierarchy determination as function of the fraction of the full $\delta$ range $0^\circ-360^\circ$ within which CP violation can be discovered.

Mass hierarchy performance versus the fraction of $\delta_{CP}$ parameter.
LENF, C2Py1, C2Py2, SPL2, ESS, T2HK and LBNE stand for Low Energy Neutrino Factory (2000 km, 100 kt MIND), CERN to Pyhasalmi (SPS, 2300 km, 20 kt resp. 200 kt LAr), SPL to Canfranc (650 km, 500 kt WC), ESS Super Beam (400 km, 500 kt WC), T2HK Japan project and LBNE USA long baseline, respectively.

(Enrique Fernandez)

For these first evaluations, the target, horn and decay tunnel parameters, had not been optimized for the ESS proton driver energy of 2.5 GeV. Inclusion of atmospheric neutrinos in the mass hierarchy determination will certainly also improve the physics reach of this project.
The diagram shows the fraction of $\delta$ as a function of $L$ [Km] for different energies: 3 GeV, 3.5 GeV, 4 GeV, 2.5 GeV. The curves indicate the standard deviation with $3\sigma$ and $5\sigma$ significance levels.