The European Spallation Source Neutrino Super Beam for CP Violation discovery

Marcos DRACOS
IPHC-IN2P3/CNRS Université de Strasbourg
August 14, 2015
under construction phase
(~1.85 B€ facility)
Having access to a powerful proton beam...

What can we do with:

- 5 MW power
- 2 GeV energy
- 14 Hz repetition rate
- $10^{15}$ protons/pulse
- $>2.7 \times 10^{23}$ protons/year

conventional neutrino (super) beam
ESSvSB neutrino energy distribution

neutrinos

anti-neutrinos

almost pure $\nu_\mu$ beam

<table>
<thead>
<tr>
<th></th>
<th>positive</th>
<th>negative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_\nu ,(\times 10^{10})/m^2$</td>
<td>$N_\nu ,(\times 10^{10})/m^2$</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>396</td>
<td>11</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>6.6</td>
<td>206</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>1.9</td>
<td>0.04</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>0.02</td>
<td>1.1</td>
</tr>
</tbody>
</table>

at 100 km from the target and per year (in absence of oscillations)
Can we go to the 2nd oscillation maximum using our proton beam?

Yes, if we place our far detector at around 500 km from the neutrino source.

MEMPHYS Cherenkov detector
(MEGaton Mass PHYSics studied by LAGUNA)

- Neutrino Oscillations (Super Beam, Beta Beam)
- Proton decay
- Astroparticles
  - Understand the gravitational collapsing: galactic SN
  - Supernovae "relics"
- Solar Neutrinos
- Atmospheric Neutrinos

- 500 kt fiducial volume (~20xSuperK)
- Readout: ~240k 8” PMTs
- 30% optical coverage

(arXiv: hep-ex/0607026)
Neutrino spectra

540 km (2 GeV) below $\nu_\tau$ production

$\delta_{CP}=0$

$\nu_e$ signal
$\nu_\mu$ missID
$\nu_e$ beam
$\overline{\nu}_e$ beam
NC back.
$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

$\nu_e$ signal
$\overline{\nu}_e$ missID
$\nu_e$ beam
$\overline{\nu}_e$ beam
NC back.
$\nu_\mu \rightarrow \nu_e$

2 years
8 years

M. Dracos IPHC/IN2P3-CNRS-UNISTRA
2nd Oscillation max. coverage

2nd oscillation max. well covered by the ESS neutrino spectrum

1st oscillation max.

$\delta=\pi/2$

$\delta=-\pi/2$

$\delta=0$

$E = 2 \text{ GeV}$

$L = 540 \text{ km}$
Where to find all these protons?

European Spallation Source Linac
The ESS will be a copious source of spallation neutrons
• 5 MW average beam power
• 125 MW peak power
• 14 Hz repetition rate (2.86 ms pulse duration, $10^{15}$ protons)
• 2.0 GeV protons (up to 3.5 GeV with linac upgrades)
• $>2.7 \times 10^{23}$ p.o.t/year

Linac ready by 2023 (full power and energy)
How to add a neutrino facility?

- The neutron program must not be affected and if possible synergetic modifications
- Linac modifications: double the rate (14 Hz $\rightarrow$ 28 Hz), from 4% duty cycle to 8%.
- Accumulator (C~400 m) needed to compress to few $\mu$s the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
  - H$^-$ source (instead of protons)
  - space charge problems to be solved
- $\sim$300 MeV neutrinos
- Target station (studied in EUROv)
- Underground detector (studied in LAGUNA)
- Short pulses ($\sim$$\mu$s) will also allow DAR experiments (as those proposed for SNS)

neutrino flux at 100 km (similar spectrum than for EU FP7 EUROv SPL SB)
Previous Expertise

- ESSvSB
- EUROv (2008-2012)
- ISS (2005-2007)
- LAGUNA (2008-2010)
- LAGUNA-LBNO (2010-2014)
- BENE (2004-2008)
- SNS (USA)
Mitigation of high power effects
(4-Target/Horn system for EUROnu Super Beam)

Packed bed canister in symmetrical transverse flow configuration (titanium alloy spheres)

4-target/horn system to mitigate the high proton beam power (4 MW) and rate (50 Hz)

target inside the horn
Energy Deposition from secondary particles, 3 horns, ESSvSB -1.6 MW/EUROnu -1.3 MW

\[ P_{tg} = 212/104 \text{ kW} \]

\[ P_h = 52/32 \text{ kW} \]

(N. Vassilopoulos)

- Large increase of power (~x2) deposited on target @ ESS

Target Ti = 65% d_Ti, R_Ti = 1.5 cm

- 6.3/3.4 kW, t=10 mm
- 13.6/9.4 kW
- 21/12.4 kW, t=10 mm
- 2.4/1.7 kW
- 2.1/1.2 kW
- 2.8/1.6 kW

Horn max radial profile of power density kW/cm³

FLUKA 2014, flair
General Layout of the target station
(copied from EUROnu)
• PSU: 8 times 4x44 kA modules
• 1-charger/capacitor/coil, 4-switches per 4x44 kA module
• 8 strip lines merged into 4 transmission lines in-out/horn
• Large energy recuperation
Proton Beam Switchyard

• Update of the switchyard preliminarily designed for EUROv with ESS beam parameters (config.1)

• Other possible layouts currently being studied (i.e config.2)

• Selection criteria: number of magnetic elements needed + type of operation (i.e. simple or bi-polar) + prospective of beam dump requirements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EUROv</th>
<th>ESSvSB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle</td>
<td>H^-</td>
<td>H^-</td>
</tr>
<tr>
<td>Proton kinetic energy (GeV)</td>
<td>4.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Pulse intensity (mA)</td>
<td>40</td>
<td>62.5</td>
</tr>
<tr>
<td>Avg beam power (MW)</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Beam rigidity (Tm)</td>
<td>17.85</td>
<td>11.02</td>
</tr>
<tr>
<td>Macro-pulse length (linac) (ms)</td>
<td>2.86</td>
<td>0.715</td>
</tr>
<tr>
<td>Pulse length (accu.) (μs)</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Pulse repetition rate (Hz)</td>
<td>50</td>
<td>70</td>
</tr>
</tbody>
</table>

Total length: **43.4 m**
Max. B-field: 0.65 T (25 kA turns / pole)
Dipole length: 2 m

Total length: **72.2 m**
Max. B-field: 0.73 T (29 kA turns / pole)
Dipole length: 2 m

config1.

config2.
Proton Beam Switchyard

Assumptions:
- Norm. trans. Emittances: 225 μm (99.7%)
- Momentum dispersion: 0.1% rms.

<table>
<thead>
<tr>
<th>Quadrupole</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field gradient, T/m</td>
<td>1.9</td>
<td>-2.4</td>
<td>1.1</td>
</tr>
<tr>
<td>Intensity, NI per pole, kA</td>
<td>30.8</td>
<td>39.0</td>
<td>17.8</td>
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</table>

<table>
<thead>
<tr>
<th>Quadrupole</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
<th>Q5</th>
<th>Q6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grad., T/m</td>
<td>1.7</td>
<td>-3.0</td>
<td>1.7</td>
<td>2.6</td>
<td>-3.6</td>
<td>2.0</td>
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<tr>
<td>Intensity, NI / pole, kA</td>
<td>27.2</td>
<td>48.3</td>
<td>28.5</td>
<td>41.8</td>
<td>59.9</td>
<td>33.7</td>
</tr>
</tbody>
</table>

> IPAC’15 Proceedings: E. Bouquerel, “Design Status of the ESSnuSB Switchyard”, MOPWA017
Rio, August 2015
M. Dracos IPHC/IN2P3-CNRS-UNISTRA
ESSvSB layout
(adopted from EUROnu Super Beam, inspired by J-PARC (T2K))

Switching yard to four proton beams or accumulator rings

Iron (2.2 m) and concrete (3.7 m) shielding

Concrete surrounding shielding (8 m)

Concrete surrounding shielding (8 m)

Decay tunnel (He vessel (25 m))

4-targets/horns Vessel (He)

PSU

Beam dump

EUROnu arXiv:1212.0732
Avoid sharper bends
Switch from 2.5 GeV linac

Drift-space between quads before dogleg ~ 6.6 m

Drift-space between quads before dogleg ~ 6.6 m
The ESSnuSB Accumulator

- 376 m long ring as one of the possible layout
- Stripping foil injection: Temperature of the foils currently under studies

Summary of Lattice Parameters for the Accumulator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>376 m</td>
</tr>
<tr>
<td>Number of dipoles</td>
<td>64</td>
</tr>
<tr>
<td>Number of quadrupoles</td>
<td>84</td>
</tr>
<tr>
<td>Bending radius</td>
<td>14.6 m</td>
</tr>
<tr>
<td>Injection region</td>
<td>12.5 m</td>
</tr>
<tr>
<td>Revolution time</td>
<td>1.32 μs</td>
</tr>
</tbody>
</table>

Maximum foil temperatures:

- 1797 K (H-Linac Beam)
- 2050 K (H-+p circulating Beam)

J. Jonnerby, CERN

H. Schönauer, CERN

> IPAC’15 Proceedings: E. Wildner et al., “The Accumulator of the ESSnuSB for Neutrino Production”, THPF100
Río, August 2015
M. Dracos IPHC/IN2P3-CNRS-UNISTRA
Possible locations for far detector

<table>
<thead>
<tr>
<th>Location</th>
<th>Baseline from CERN (km)</th>
<th>Baseline from Protvino (km)</th>
<th>Baseline from ESS (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyhäsalmen, FI</td>
<td>2300</td>
<td>1160</td>
<td>1140</td>
</tr>
<tr>
<td>Zinkgruvan, SE</td>
<td>1530</td>
<td>1420</td>
<td><strong>360</strong></td>
</tr>
<tr>
<td>Garpenberg, SE</td>
<td>1730</td>
<td>1300</td>
<td><strong>540</strong></td>
</tr>
<tr>
<td>Kristineberg, SF</td>
<td>2230</td>
<td>1530</td>
<td>1080</td>
</tr>
<tr>
<td>Björkdal, SE</td>
<td>2270</td>
<td>1450</td>
<td>1100</td>
</tr>
<tr>
<td>Munka, SE</td>
<td>2310</td>
<td>1620</td>
<td>1160</td>
</tr>
<tr>
<td>Kallak, SE</td>
<td>2400</td>
<td>1700</td>
<td>1260</td>
</tr>
<tr>
<td>Malmsberg, SE</td>
<td>2480</td>
<td>1620</td>
<td>1320</td>
</tr>
<tr>
<td>Kiirunavaara, SE</td>
<td>2530</td>
<td>1700</td>
<td>1380</td>
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<td>Kaunisvaara, SE</td>
<td>2552</td>
<td>1580</td>
<td>1390</td>
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<tr>
<td>Kongsberg, NO</td>
<td>1536</td>
<td>1740</td>
<td><strong>500</strong></td>
</tr>
<tr>
<td>Løkken, NØ</td>
<td>1900</td>
<td>1800</td>
<td>840</td>
</tr>
</tbody>
</table>

LAGUNA sites
Which baseline?

- Zinkgruvan is better for 2 GeV
- Garpenberg is better for > 2.5 GeV
- **systematic errors**: 5%/10% (signal/backg.)

- Zinkgruvan is better
- atmospheric neutrinos are needed (at least at low energy)
ESS Neutrino Super Beam DS

A very intense neutrino super beam experiment for leptonic CP violation discovery based on the European spallation source linac

E. Baussan\textsuperscript{m}, M. Blennow\textsuperscript{i}, M. Bogomilov\textsuperscript{k}, E. Bouquerel\textsuperscript{m}, O. Caretta\textsuperscript{c}, J. Cederkäll\textsuperscript{f}, P. Christiansen\textsuperscript{f}, P. Coloma\textsuperscript{b}, P. Cupial\textsuperscript{c}, H. Danared\textsuperscript{g}, T. Davenne\textsuperscript{c}, C. Densham\textsuperscript{c}, M. Dracos\textsuperscript{m,*}, T. Ekelöf\textsuperscript{h,*}, M. Eshraqi\textsuperscript{g}, E. Fernandez Martinez\textsuperscript{b}, G. Gaudiot\textsuperscript{m}, R. Hall-Wilton\textsuperscript{g}, J.-P. Koutchouk\textsuperscript{n,d}, M. Lindroos\textsuperscript{g}, P. Loveridge\textsuperscript{e}, R. Matev\textsuperscript{k}, D. McGinnis\textsuperscript{g}, M. Mezzetto\textsuperscript{j}, R. Miyamoto\textsuperscript{e}, L. Mosca\textsuperscript{i}, T. Ohlsson\textsuperscript{i}, H. Öhman\textsuperscript{n}, F. Osswald\textsuperscript{m}, S. Peggs\textsuperscript{g}, P. Poussot\textsuperscript{m}, R. Ruber\textsuperscript{n}, J.Y. Tang\textsuperscript{a}, R. Tsenev\textsuperscript{k}, G. Vankova-Kirilova\textsuperscript{k}, N. Vassilopoulos\textsuperscript{m}, D. Wilcox\textsuperscript{c}, E. Wildner\textsuperscript{d}, J. Wurtz\textsuperscript{m}

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\textsuperscript{i} Laboratoire Souterrain de Modane, F-73500 Modane, France
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\textsuperscript{k} Department of Atomic Physics, St. Kliment Ohridski University of Sofia, Sofia, Bulgaria
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\textsuperscript{n} Department of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden

14 participating institutes from 10 different countries, among them ESS and CERN
Muon at the level of the beam dump

\[ 2.7 \times 10^{23} \text{ p.o.t/year} \]

- **muons** at the level of the beam dump (per proton)
- **4.2 \times 10^{20} \mu/\text{year}** (16.3 \times 10^{20} for 4 m²)
- **4.1 \times 10^{20} \mu/\text{year}**

- input beam for future 6D \( \mu \) cooling experiments (for muon collider)
- good to measure neutrino x-sections \((\nu_\mu, \nu_e)\) around 200-300 MeV (low energy nuSTORM)
• A **H2020** Design Study has been submitted last September
  • 11 institutes (including ESS and CERN) from 8 European countries
  • Decision:
    • Overall score 13.5/15 (5/5 for Excellence)
    • not enough to be funded (only 15 MEUR for this call)
    • nevertheless, the evaluators recognise that **ESSνSB answers one of the priorities defined in the European Strategy for Particle Physics**.

• New funding sources are now investigated in order to continue this design study (probably re-apply to H2020 2016/2017 call).

• Some studies for H⁻ injection and accumulation ring are included in an approved EU project concerning High Brightness neutron facility.
ESS under construction
ESS Construction

February 2015

- First proton beam by 2019
- Full power/energy by 2023
Conclusion

• Significantly better CPV sensitivity at the 2nd oscillation maximum.
• The European Spallation Source Linac will be ready in less than 10 years (5 MW, 2 GeV proton beam by 2023)
• Neutrino Super Beam based on ESS linac is very promising.
• ESS will have enough protons to go to the 2nd oscillation maximum and increase its CPV sensitivity.
• CPV: 5σ could be reached over 60% of δCP range (ESSνSB) with large potentiality.
• Large associated detectors have a rich astroparticle physics program.
• Full complementarity with a long baseline experiment on the 1st oscillation maximum using another detection technique (LAr?).
• A Design Study is urgently needed.
Neutrino Oscillations with "large" $\theta_{13}$

$P(\nu_\mu \rightarrow \nu_e)$

1st oscillation maximum

- $\theta_{13}=1^\circ$ ("small" $\theta_{13}$)
- $\delta_{CP}=-90$
- $\delta_{CP}=0$
- $\delta_{CP}=+90$

2nd oscillation maximum

- $\theta_{13}=8.8^\circ$ ("large" $\theta_{13}$)

for small $\theta_{13}$

1st oscillation maximum is better

($\theta_{13}=1^\circ$)

for "large" $\theta_{13}$

1st oscillation maximum is dominated by atmospheric term

- 1st oscillation max.: $A=0.3\sin\delta_{CP}$
- 2nd oscillation max.: $A=0.75\sin\delta_{CP}$

more sensitivity at 2nd oscillation max.

DAR experiments (ESS/SNS)

Typical expected supernova neutrino spectrum for different flavours (solid lines) and SNS/ESS neutrino spectrum (dashed and dotted lines)
Neutrino Oscillations with "large" $\theta_{13}$

- at the 1$^{\text{st}}$ oscillation max.: $A = 0.3\sin\delta_{\text{CP}}$
- at the 2$^{\text{nd}}$ oscillation max.: $A = 0.75\sin\delta_{\text{CP}}$


$2^{\text{nd}}$ oscillation maximum is better
## Systematic errors

<table>
<thead>
<tr>
<th>Systematics</th>
<th>SB</th>
<th></th>
<th></th>
<th>BB</th>
<th></th>
<th></th>
<th>NF</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial volume ND</td>
<td>0.2%</td>
<td>0.5%</td>
<td>1%</td>
<td>0.2%</td>
<td>0.5%</td>
<td>1%</td>
<td>0.2%</td>
<td>0.5%</td>
<td>1%</td>
</tr>
<tr>
<td>Fiducial volume FD (incl. near-far extrapol.)</td>
<td>1%</td>
<td>2.5%</td>
<td>5%</td>
<td>1%</td>
<td>2.5%</td>
<td>5%</td>
<td>1%</td>
<td>2.5%</td>
<td>5%</td>
</tr>
<tr>
<td>Flux error signal $\nu$</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
<td>1%</td>
<td>2%</td>
<td>2.5%</td>
<td>0.1%</td>
<td>0.5%</td>
<td>1%</td>
</tr>
<tr>
<td>Flux error background $\nu$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>correlated</td>
<td></td>
<td></td>
<td>correlated</td>
<td></td>
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</tr>
<tr>
<td>Flux error signal $\bar{\nu}$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>1%</td>
<td>2%</td>
<td>2.5%</td>
<td>0.1%</td>
<td>0.5%</td>
<td>1%</td>
</tr>
<tr>
<td>Flux error background $\bar{\nu}$</td>
<td>20%</td>
<td>30%</td>
<td>40%</td>
<td>correlated</td>
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<tr>
<td>Background uncertainty</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
</tr>
<tr>
<td>Cross secs $\times$ eff. QE$^\dagger$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
</tr>
<tr>
<td>Cross secs $\times$ eff. RES$^\dagger$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>10%</td>
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<td>20%</td>
</tr>
<tr>
<td>Cross secs $\times$ eff. DIS$^\dagger$</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
</tr>
<tr>
<td>Effec. ratio $\nu_e/\nu_\mu$ QE$^*$</td>
<td>3.5%</td>
<td>11%</td>
<td>–</td>
<td>3.5%</td>
<td>11%</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Effec. ratio $\nu_e/\nu_\mu$ RES$^*$</td>
<td>2.7%</td>
<td>5.4%</td>
<td>–</td>
<td>2.7%</td>
<td>5.4%</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Effec. ratio $\nu_e/\nu_\mu$ DIS$^*$</td>
<td>2.5%</td>
<td>5.1%</td>
<td>–</td>
<td>2.5%</td>
<td>5.1%</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Matter density</td>
<td>1%</td>
<td>2%</td>
<td>5%</td>
<td>1%</td>
<td>2%</td>
<td>5%</td>
<td>1%</td>
<td>2%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Systematic errors and exposure

for ESSnuSB systematic errors see 1209.5973 [hep-ph] (lower limit "default" case, upper limit "optimistic" case)

High potentiality

Impact of systematics
Setup: 2GeV – 360 km

(courtesy P. Coloma)
Effect of the unknown MH on CPV performance

"default" case for systematics

(P. Coloma)

Impact of unknown hierarchy

L=360 km, $E_p=2$ GeV

L=540 km, $E_p=2.5$ GeV

small effect  practically no need to re-optimize when MH will be known
\( \delta_{CP} \) accuracy performance

(USA snowmass process, P. Coloma)

\[ \Delta \delta_{CP} \text{ at } 1 \sigma \]

- IDS-NF
- NuMAX
- Hyper-K
- LBNE-PX
- LBNE-Full
- LBNE10
- LBNO-Eol
- ESS\( \nu \)SB\( ^{2}_{360} \)
- ESS\( \nu \)SB\( ^{2}_{540} \)
- 2020
- 2025

for systematic errors see (7.5%/15% for ESSnuSB):

$\delta_{CP}$ coverage

CPV (2 GeV protons)

after 10 years

with 2 times more statistics

systematic errors (nominal values): 5%/10% for signal/background

more than 50% $\delta_{CP}$ coverage using reasonable assumptions on systematic errors
The MEMPHYS Detector
(Proton decay)

(arXiv: hep-ex/0607026)
The MEMPHYS Detector
(Supernova explosion)

For 10 kpc: $\sim 10^5$ events

Diffuse Supernova Neutrinos
(10 years, 440 kt)