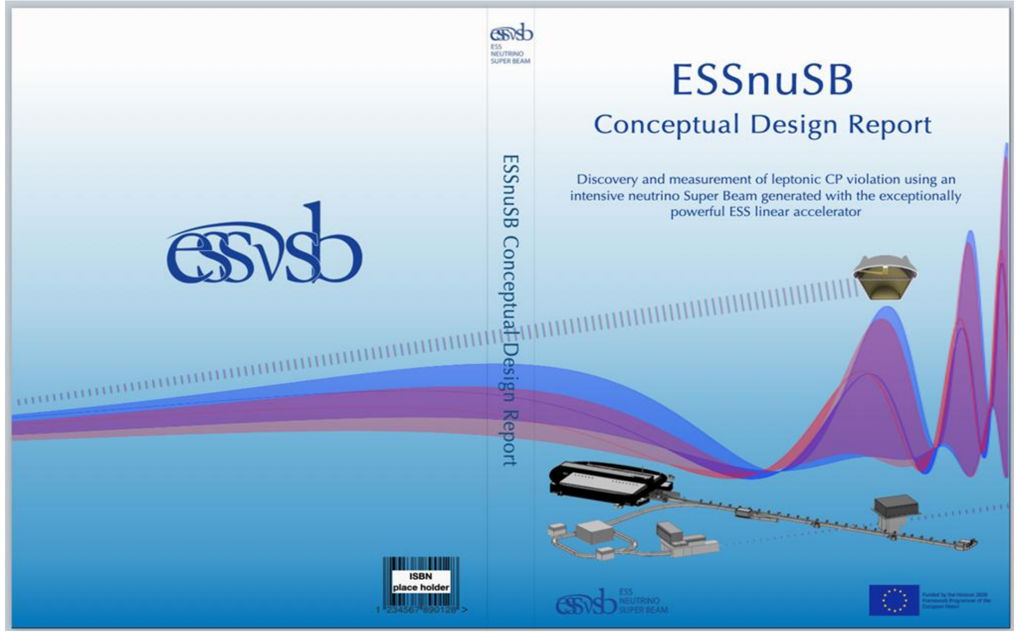
Presentation of ESSnuSB

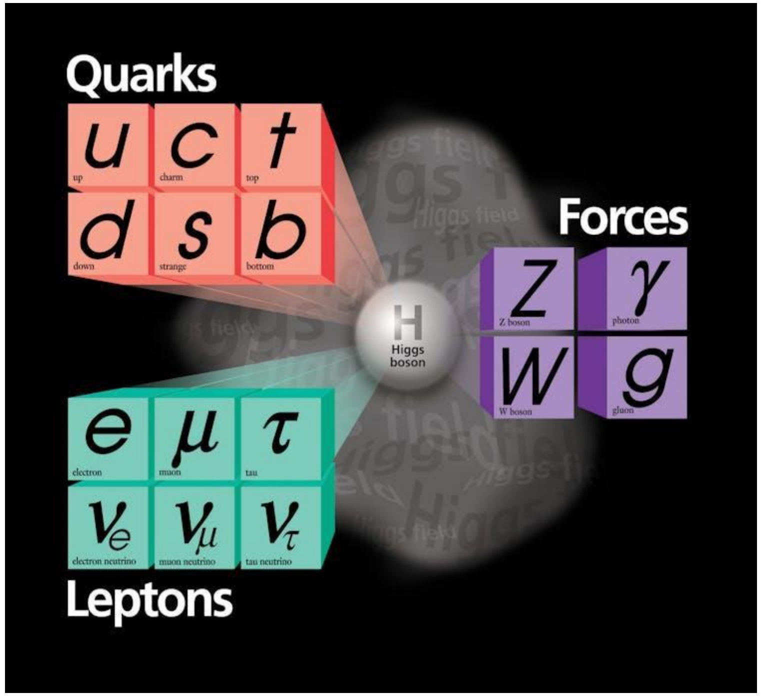
ESS neutrino Super Beam



STAP meeting at ESS 21 April 2026

On behalf of the ESSnuSB Consortium
Tord Ekelof
Uppsala University

The Standard Model of Particle Physics



The Higg Boson discovery in 2012 implied that Standard Model (SM) is complete.

A GREAT TRIUMPH! According to the SM there are no more particles to be found.

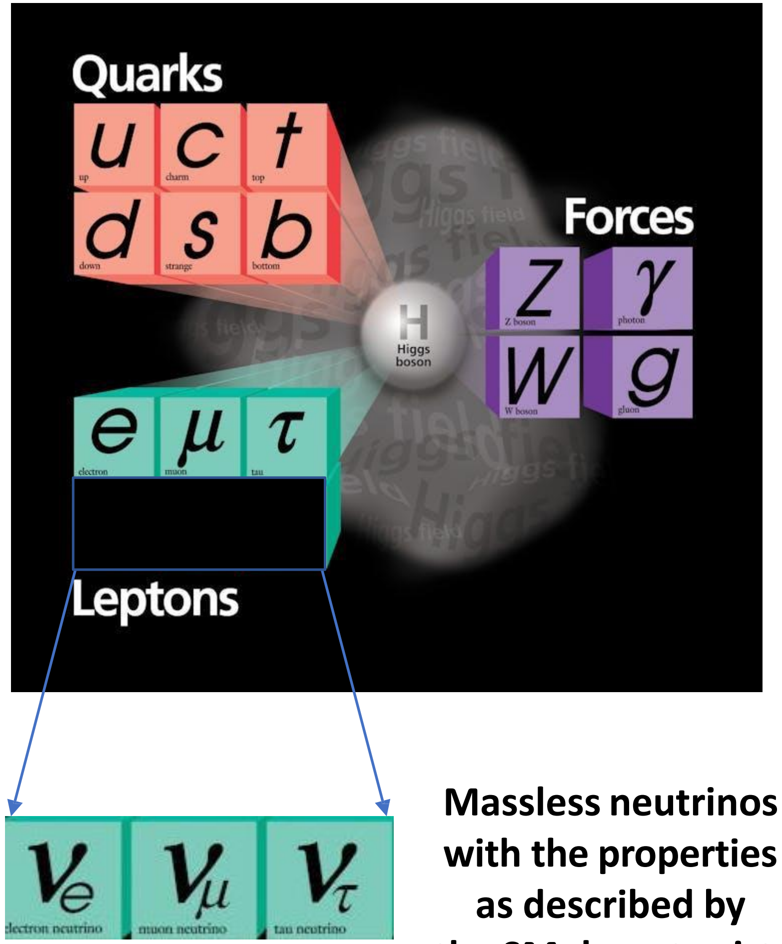
However, already since 1998, when neutrino oscillations were discovered, we know that the observed neutrinos have mass, a fact that implies that the neutrinos do not fit at all in the SM.

Furthermore, the observed Dark Matter and Dark Energy cannot be described by the SM.
And the SM does not fit with the well established General Relativity.

We need to find a new fundamental particle physics theory beyond the SM!

One way to search for a new more global theory than the SM is to search for additional particles.
But we have no clear idea of at what energy scale to search for such new particles.
The search for new particles is thus, at least currently, somewhat at random.

The Standard Model of Particle Physics



Massless neutrinos with the properties as described by the SM do not exist.

In 1998, however, we found that three particles, discovered decades ago, are not in the SM.

These particles are the neutrinos, which thereby represent a unique gateway to new physics.

The search for new particles require higher and higher collision energies. CERN is the world-leading laboratory at the "High Energy Frontier".

The neutrinos have very low mass and do not require study at the High Energy Frontier.

The neutrinos interact rarely and thus require study at the "High Intensity Frontier".

ESS with its 5 MW linac has the potential to become world-leading at the "High Intensity Frontier"

CERN and ESS are thus complementary in the search for a more global theory, beyond the SM.

European Spallation Source

ESS neutrino Super Beam plus

The Europe Spallation Source offers the possibility to elaborate a **high intensity neutrino superbeam in Europe**

LINAC Upgrades

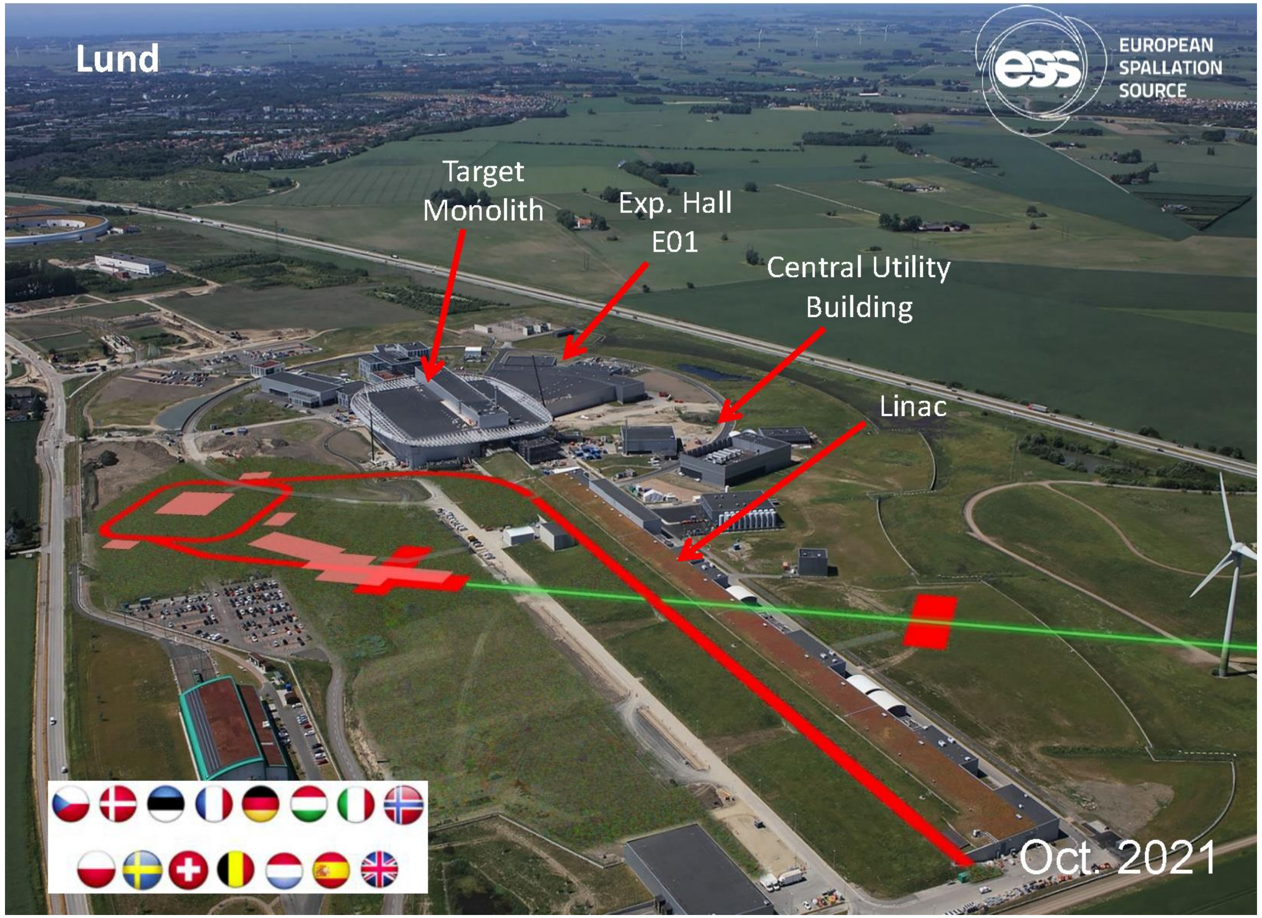
- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power => 10 MW
- 125 MW peak power unchanged.
- 14 =>28 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4% => Duty cycle 8%
- 2.0 GeV kinetic energy protons => 2.5 GeV

Additional Facilities

- Accumulator ring to shorten the pulses to μs order for the horn (Extra H^- source are. needed).
- Target Station to convert the 5 MW proton beam into neutrinos.
- Near and Far detectors.

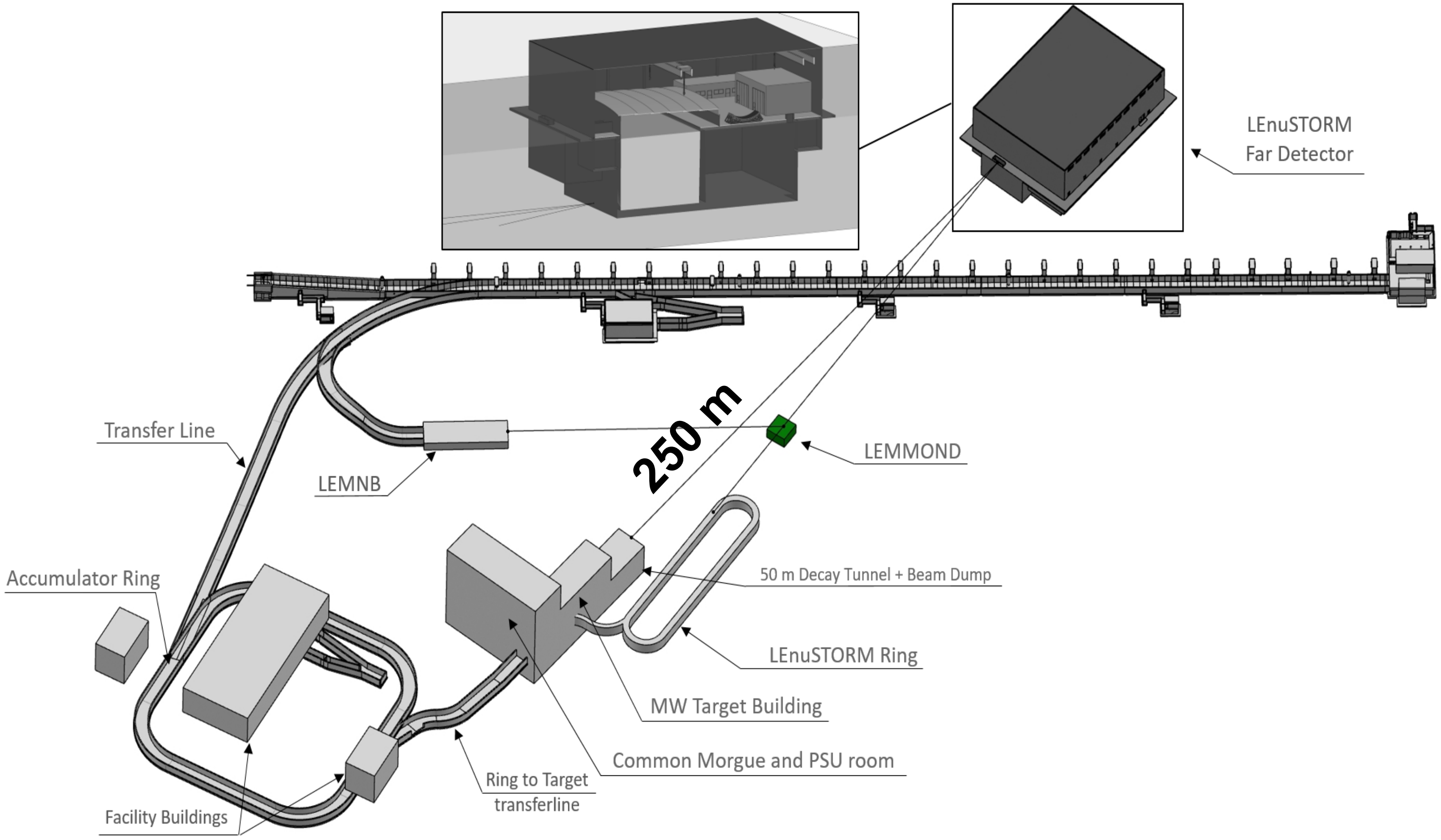
$\Rightarrow$ ESSnuSB/ESSnuSB+ projects funded by EU and 11 European Governmental research agencies

These facilities has to be in agreement with the regulation rules and environmental constraints in Sweden.



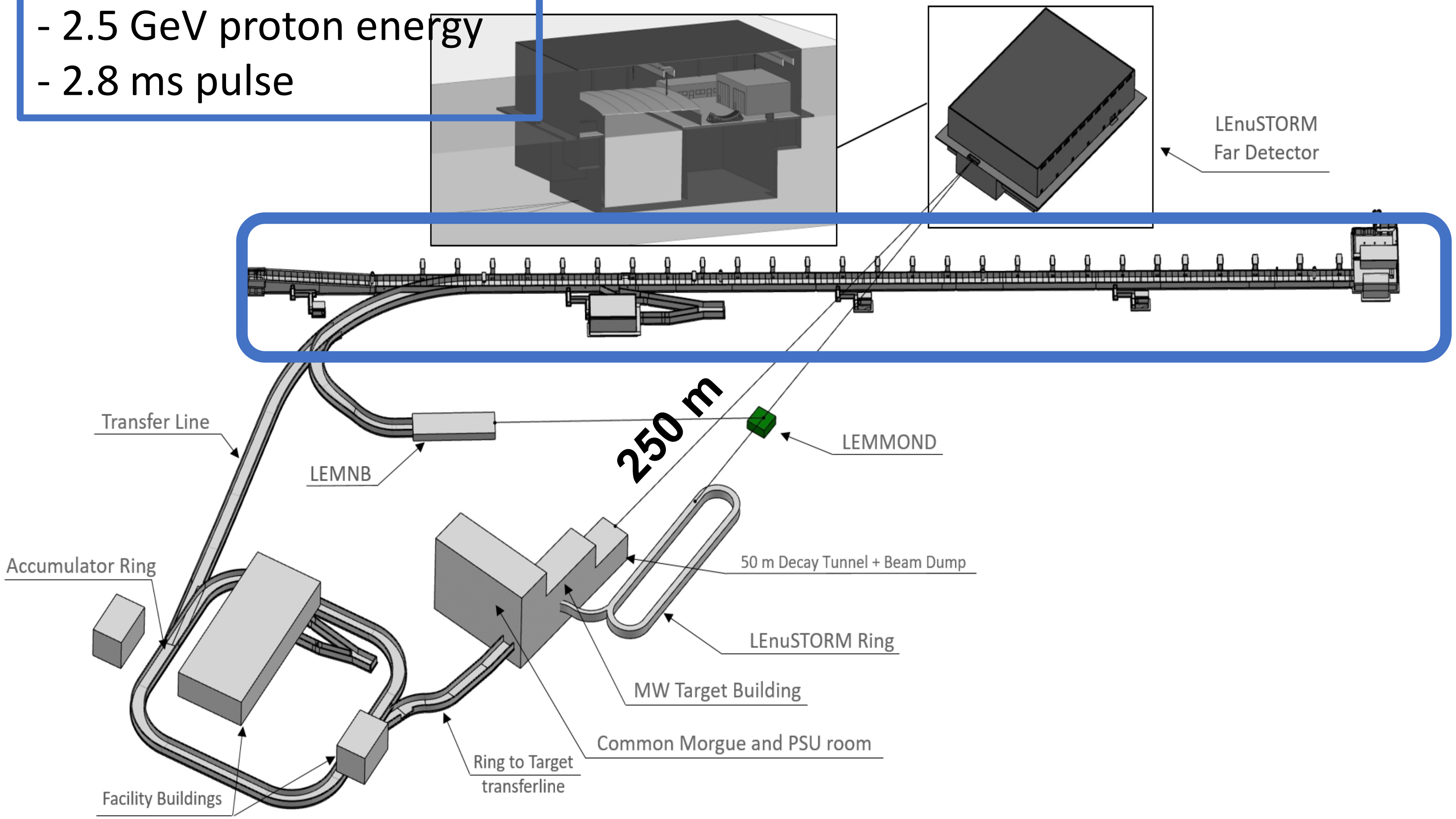
Implementation of the Facility on ESS

ESSnuSB+ setup



ESSnuSB+ setup

1. Main accelarator (ESS)
- 5 MW proton beam
- 2.5 GeV proton energy
- 2.8 ms pulse



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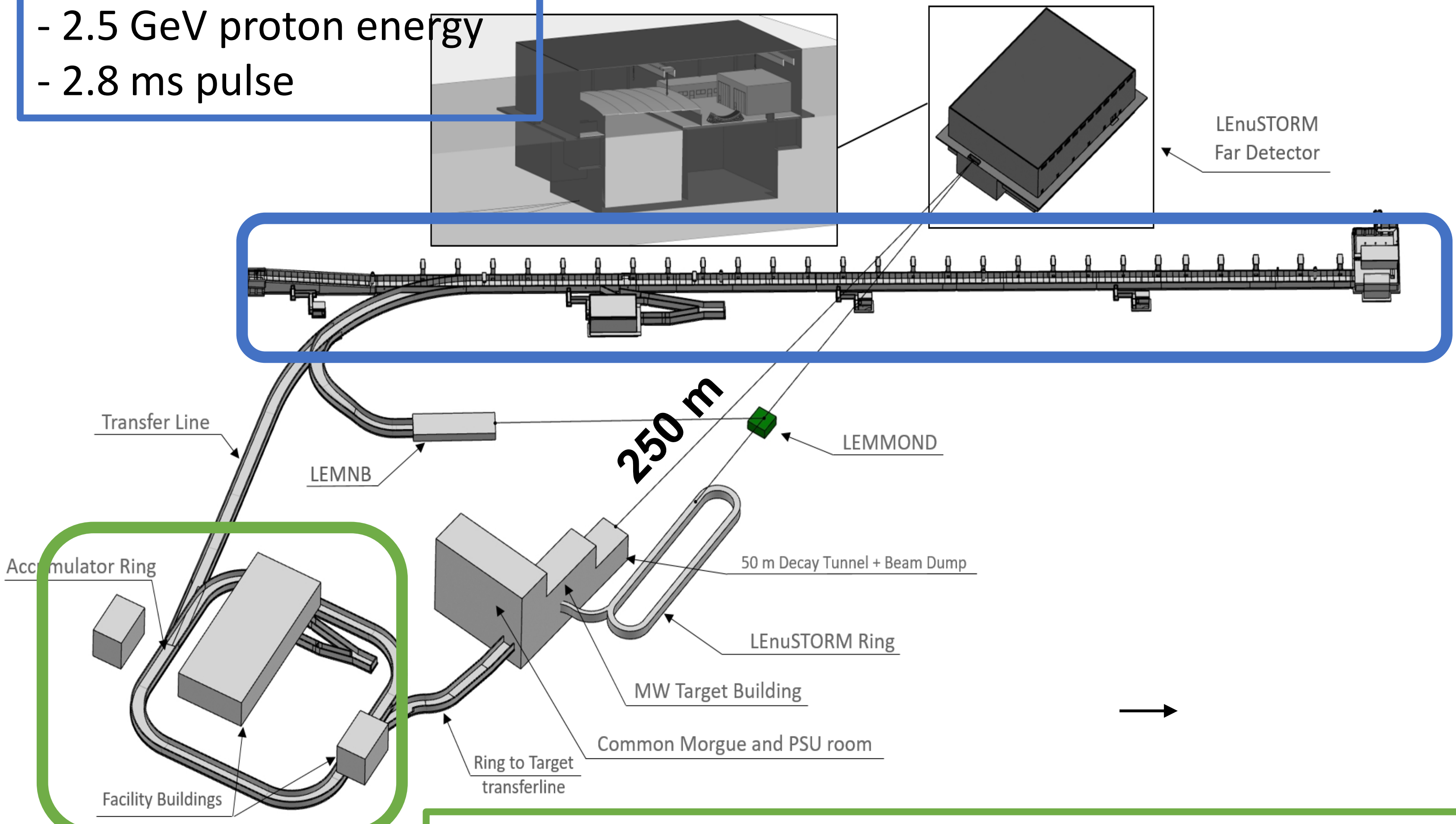

2. Accumulator – Reduces the pulse 1.2 µs (to minimize atmospheric background)

ESSnuSB+ setup

1. Main accelarator (ESS)
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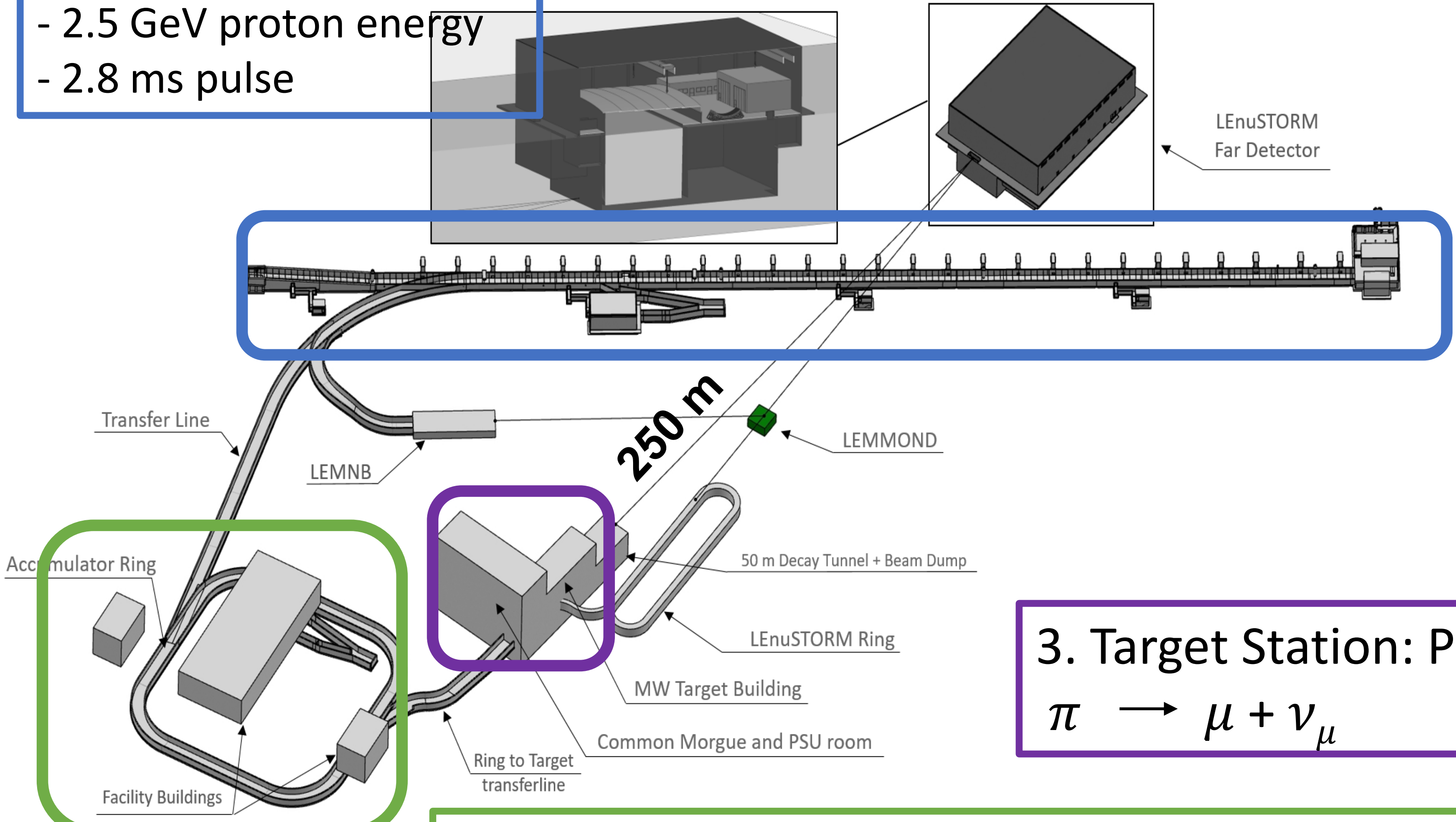


3. Target Station: Protons collide to produce π

$$\pi \longrightarrow \mu + \nu_{\mu}$$

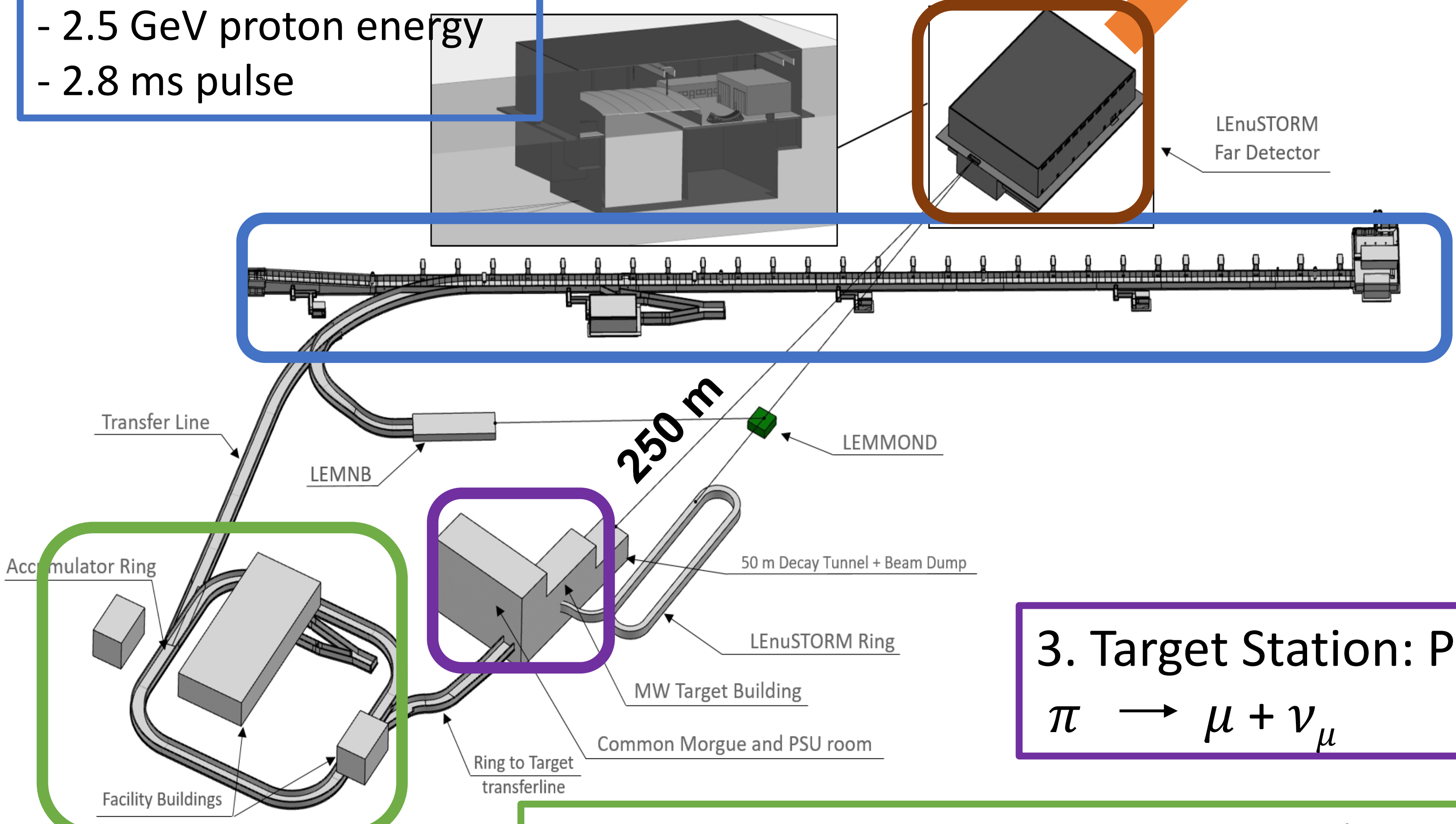
2. Accumulator – Reduces the pulse 1.2 µs (to minimize atmospheric background)

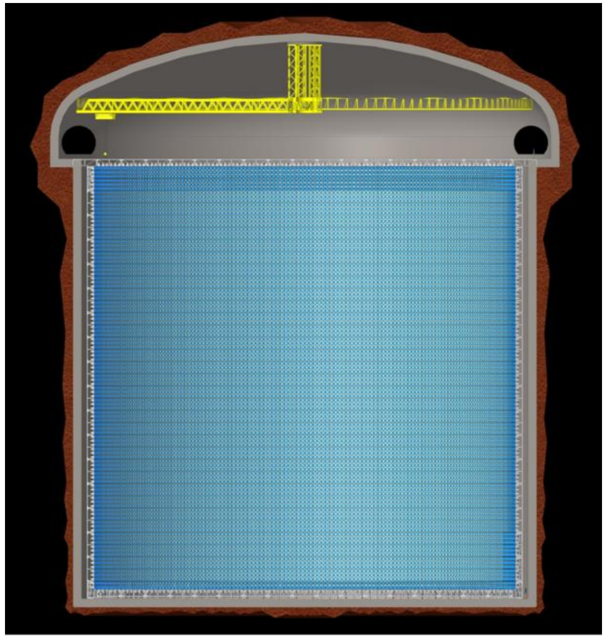
ESSnuSB+ setup

1. Main accelarator (ESS)
- 5 MW proton beam
- 2.5 GeV proton energy
- 2.8 ms pulse

4. Near Detector (END)

5. Far Detector (FD)
- 540 kt water cerenkov





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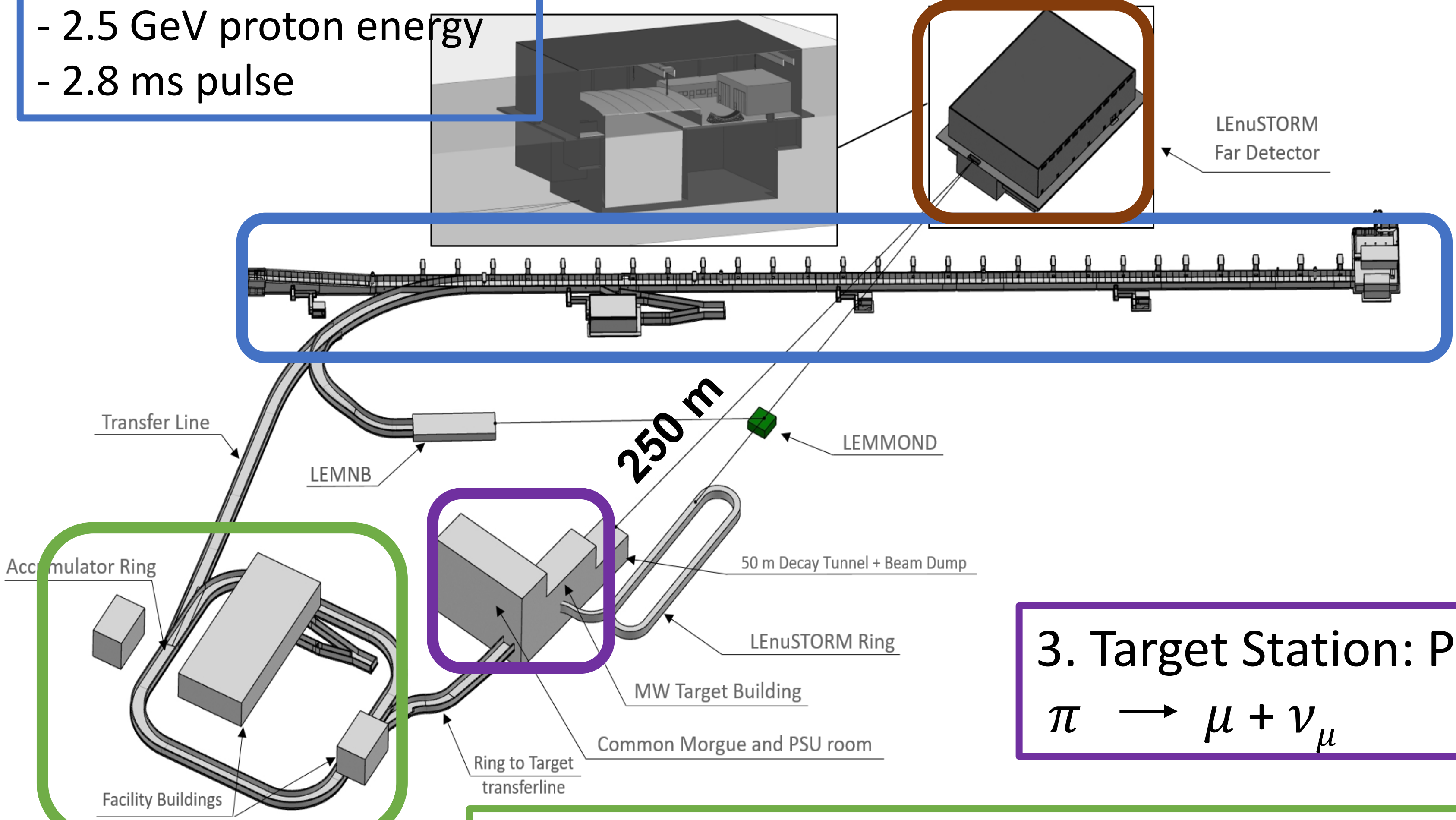

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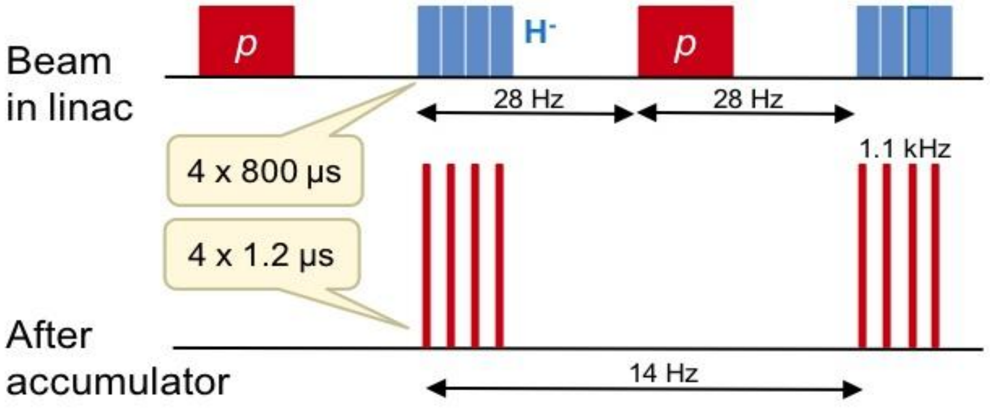
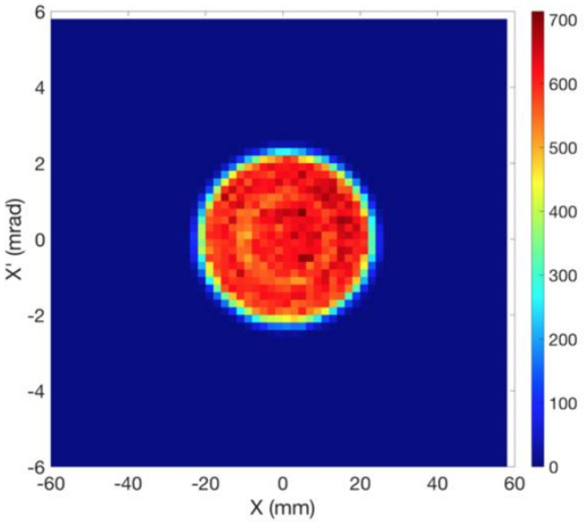
ESSνSB : ESS Upgrades

Linac Upgrade

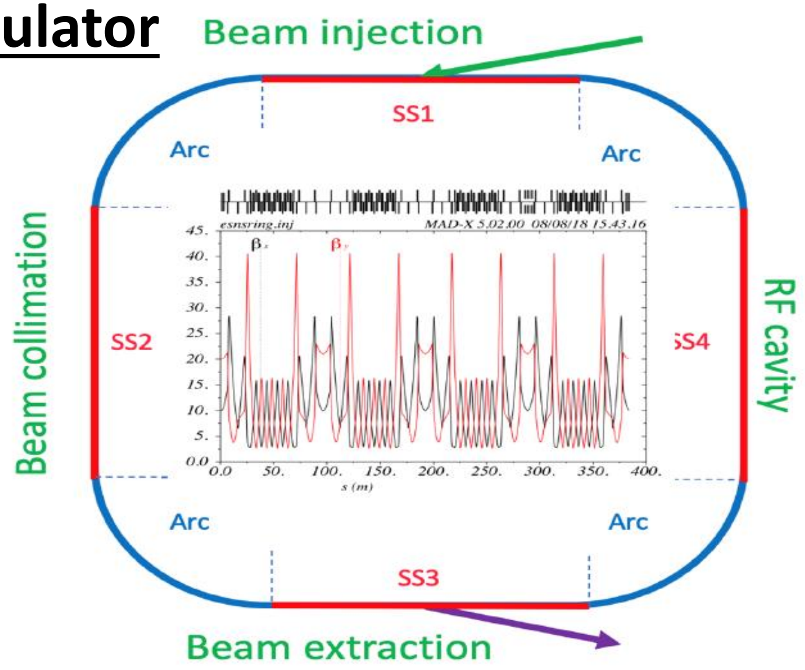


Injection

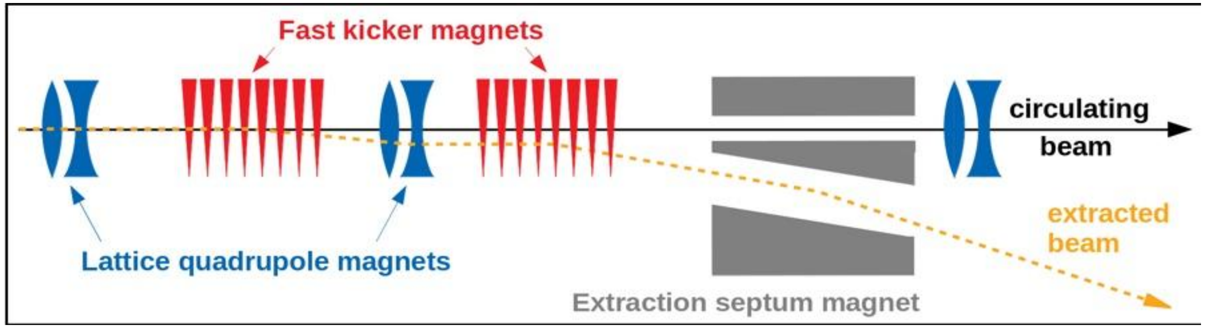
- **Foil stripping:** widely used in proton synchrotrons or accumulators, very challenging due to high power.
- **Laser stripping:** a promising alternative method (ongoing development at SNS).
- **Direct proton Injection:** under study at ESS



Accumulator

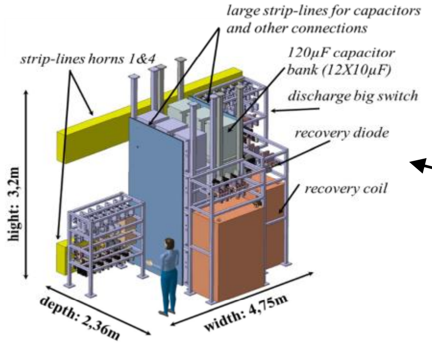


Ring-to-switchyard transfer liner



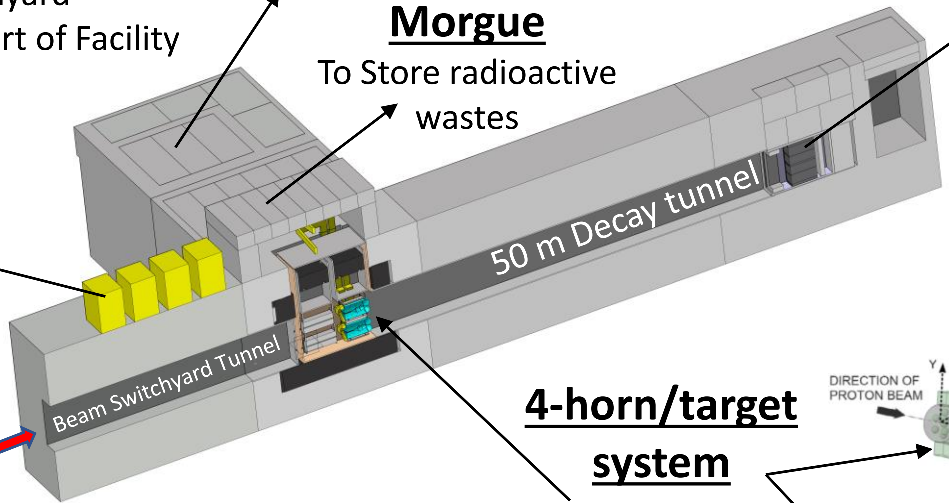
ESSνSB : 5MW Target Station

Power Supply Unit
- 16 modules (350 kA, 1.3 μs)
- Located above the switchyard
- Outside of radioactive part of Facility

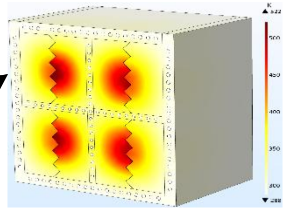


Hot Cell
- Able to manipulate/repair hadronic collector
- Work under Radioactive Environment

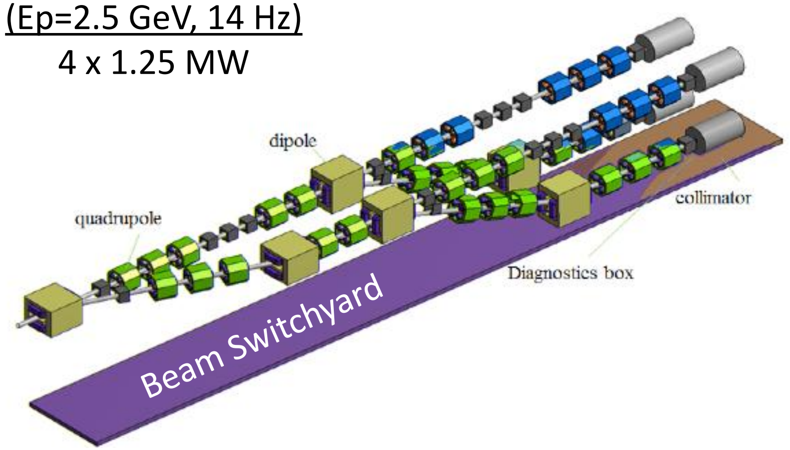
Morgue
To Store radioactive wastes



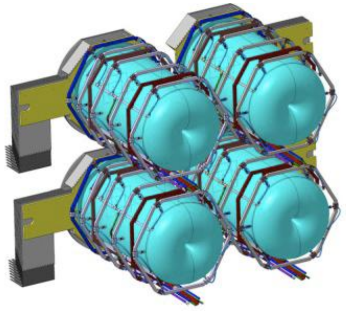
Beam dump



Proton Beam
(Ep=2.5 GeV, 14 Hz)
4 x 1.25 MW

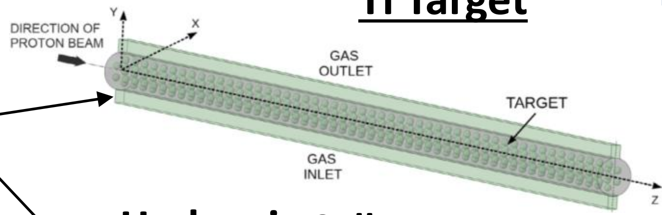


4-horn/target system

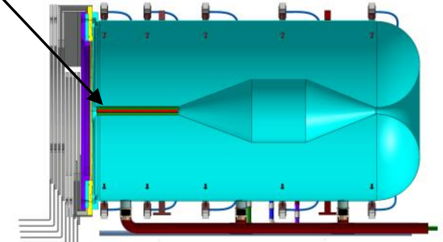


(a) The four-horn system.

Ti Target

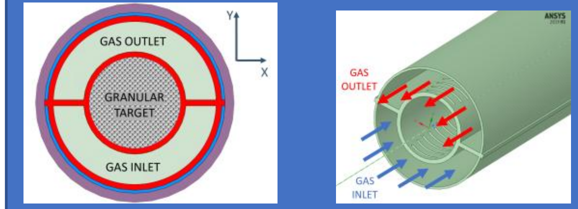


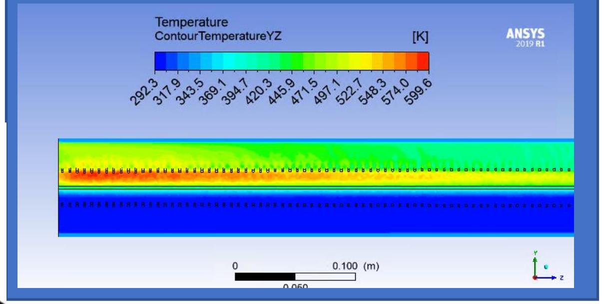
Hadronic Collector



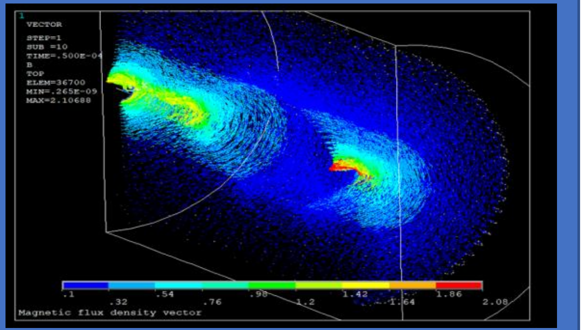
Horn

Granular Target Concept
- Target made of 3 mm titanium spheres cooled by transverse helium gas cooling





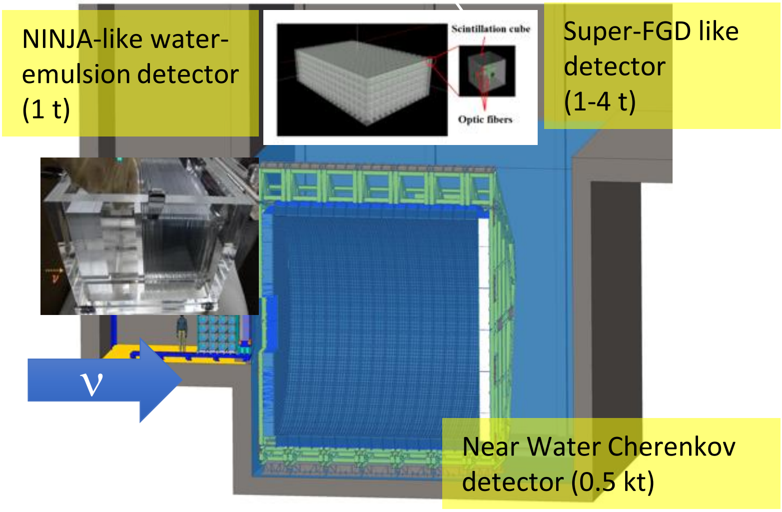
Magnetic field (350 kA; 1.3 μs pulse)



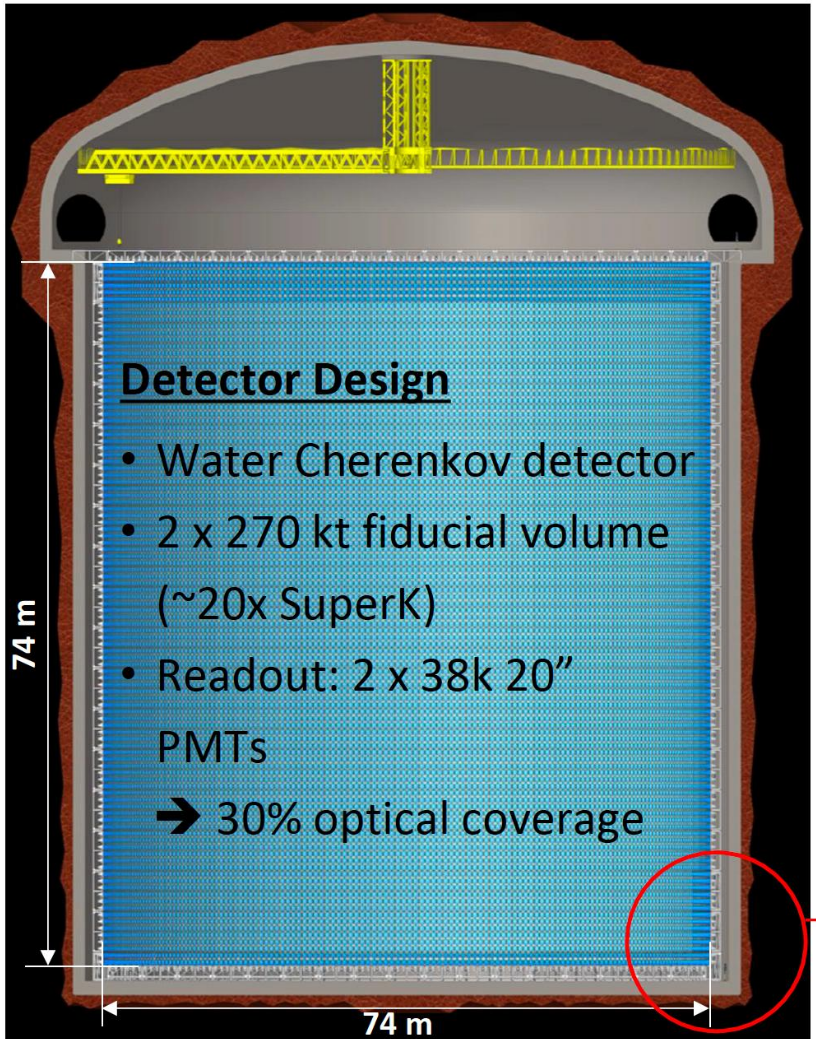
ESSνSB : Neutrino Detectors

Near Detector

- A magnetized Super Fine Grained Detector (SFGD) for cross-section measurements.
- 1 kton WC detector for event rate measurements, flux normalization and event reconstruction comparison with FD.
- Emulsion setup, similar to NINJA experiment, upstream of the SFGD, for cross-section measurements.



Far Detector

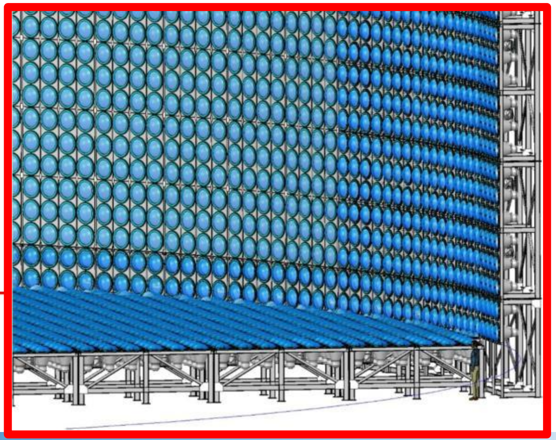


Specifications

- Baseline 360 km
- Detector diameter 74.0 m (Internal)
- Detector height 74.0 m (Internal)
- Depth (w.r.t. ground level): 1000 m

Performances

- Detector efficiency for correctly identifying neutrinos > 85%.
- Flavour misidentification probability < 1%.

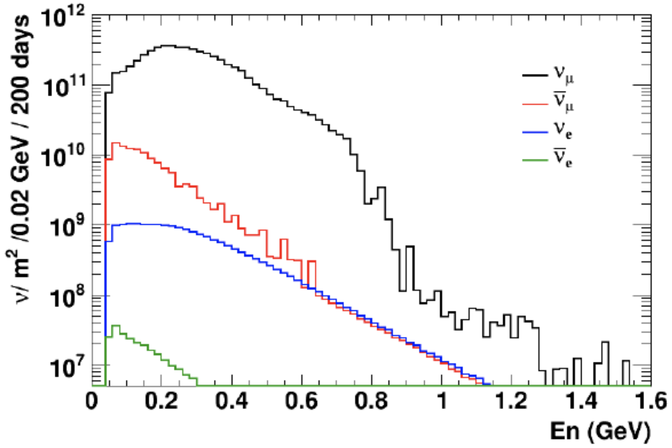


ESSνSB : Neutrino fluxes at the second oscillation maximum

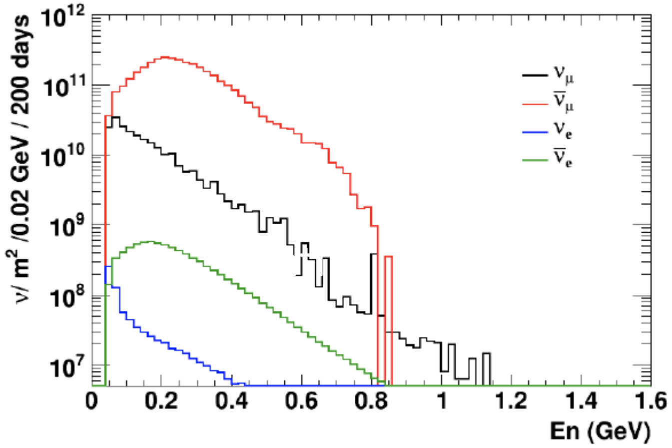
ESS neutrino Super Beam plus

Neutrino production rates

With π^- focusing



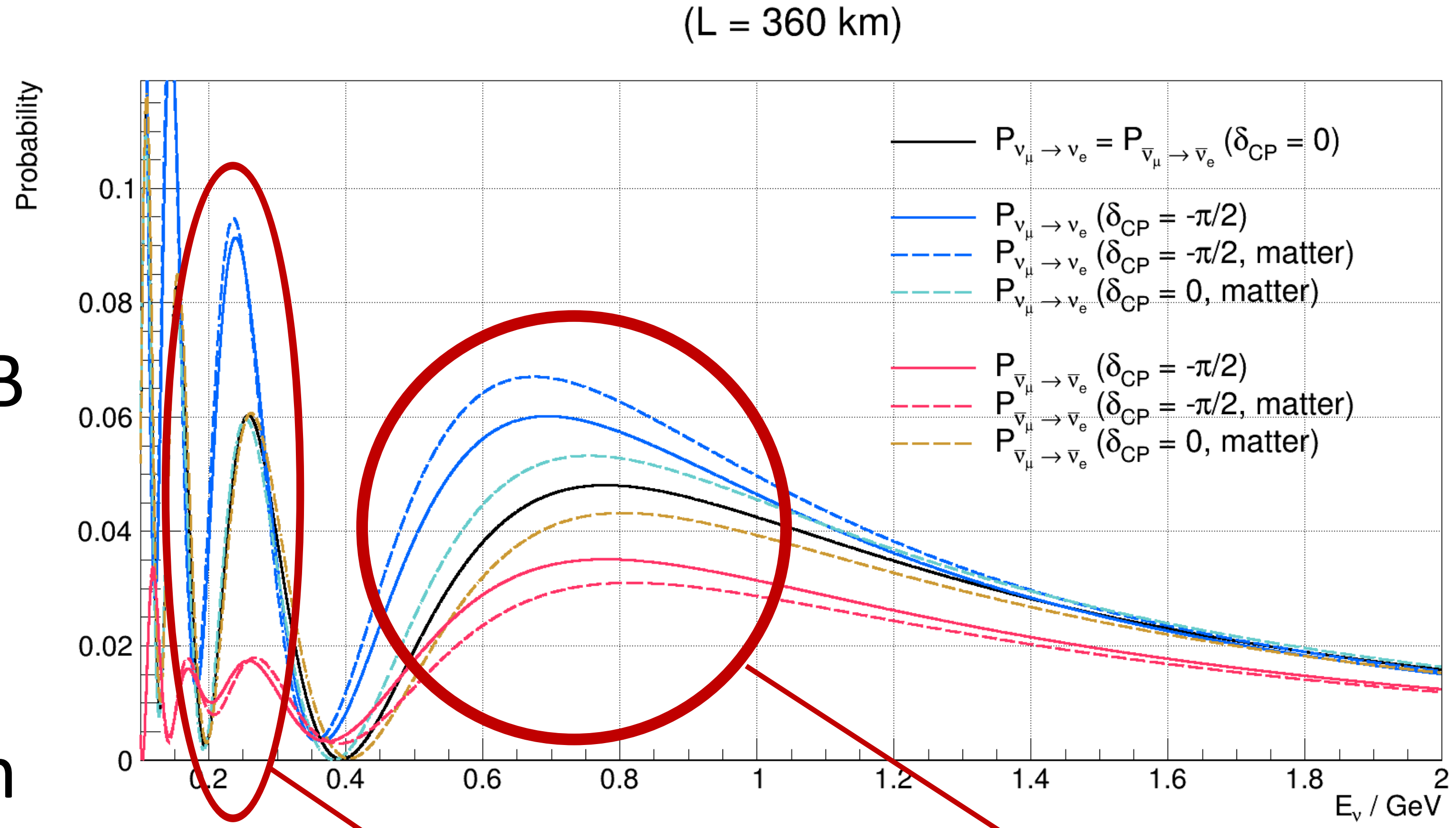
With π^+ focussing



At 360 km from the target, per year (in absence of oscillations)

The second neutrino oscillation maximum

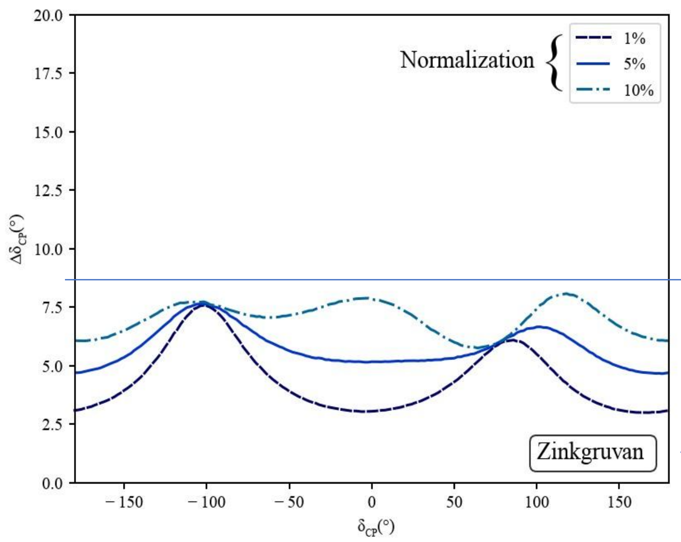
Due to the ESS world-uniquely high power 5 MW of the ESSnuSB proton beam, the ESSnuSB neutrino beam is intense enough to measure at the 3 times more distant second oscillation maxium where the CP signal close to 3 times higher.



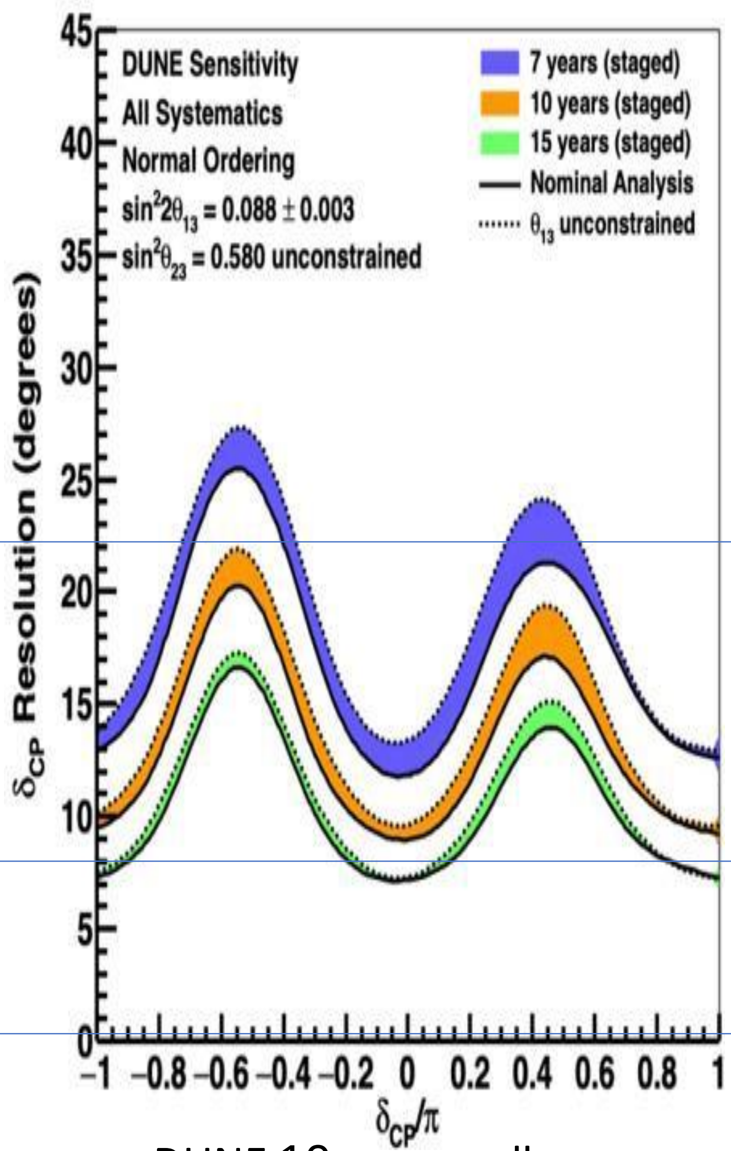
At 2nd maximum:
- larger sensitivity to δ_{CP}
- matter doesn't matter

At 1st maximum:
- smaller sensitivity to δ_{CP}
- matter can mimic CP violation

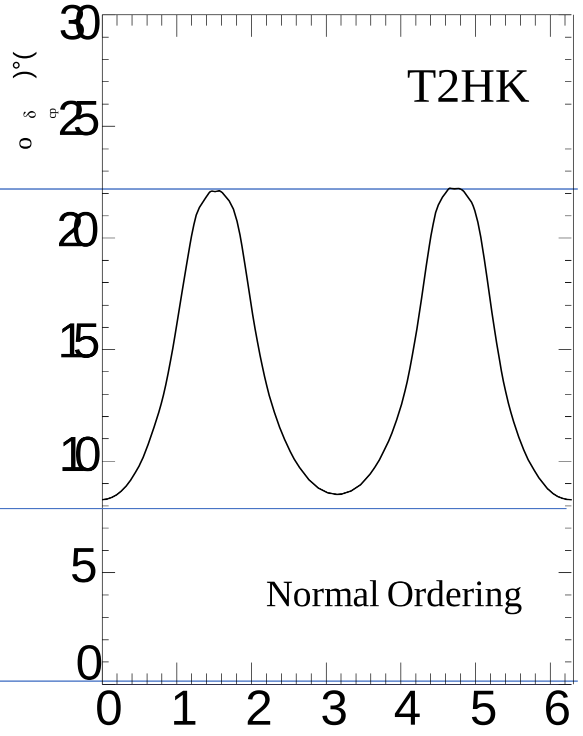
ESSnuSB in the international context – high precision in δ_{CP} due to near to 3 times higher CPV signal at the second oscillation maximum



ESSnuSB 10 years, light blue curves
https://arxiv.org/abs/2206.01208
p. 205



DUNE 10 years, yellow curve
https://arxiv.org/abs/2002.03005 p.174



HyperKamiokande 10 years
https://arxiv.org/abs/1611.06118
p. rotceted KHe no=1xKH ,60

1 October 2025

This higher sensitivity of ESSnuSB to the CPV phase δ_{CP} is recognized in the CERN Physics Briefing Book which will be input for the 2026 update of the European Strategy for Particle Physics

Electroweak Physics
Strong Interaction Physics
Flavour Physics
Beyond the Standard Model Physics:

Neutrino Physics & Cosmic Messengers: Pilar Hernandez39, Sara Bolognesi40 (Conveners), Ivan Esteban41 (Scientific Secretary), Stephen Dolan7, Valerie Domcke7, Joseph Formaggio42, M. C. Gonzalez-Garcia80,81,82, Aart Heijboer19, Aldo Ianni44, Joachim Kopp7,79, Elisa Resconi45, Mark Scott33, Viola Sordini34 (Contributors)

Beyond the Standrad Model
Dark Matter and Dark Sector
Accelerator Science and Technology
Detector Instrumentation
Theoretical Overview
Computing Reviewers

Quotation from the Neutrino Physics & Cosmic Messengers section:

” To push the physics reach beyond what is described above, various feasibility studies are being conducted for new experiments in Europe: a new gigantic reactor experiment at Chooz (SuperChooz [286]) and *a new neutrino beam to be generated using the 5 MW proton linac of the European Spallation Source (ESSnuSB [ID151]). ESSnuSB proposes to exploit the second oscillation maximum, where the CPV effect is enhanced, together with a dedicated program to measure sub-GeV cross sections*.”

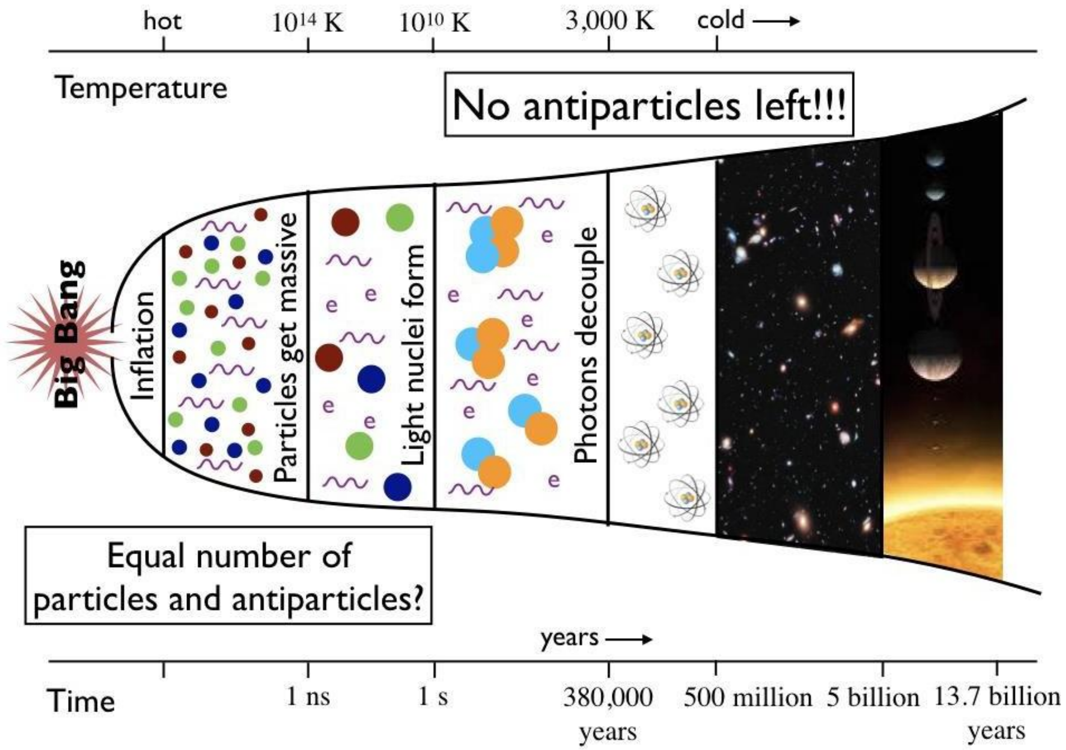
On the importance of a high δ_{CP} resolution

- Violation of CP symmetry was discovered in neutral K-meson decay in 1964. CP symmetry is thereby not, as earlier believed, an exact symmetry of Nature.

- The measured **quark CP violation in the Standard Model** cannot explain the presences of matter in the Universe (the matter density is underestimated by nine orders of magnitude), whereas a significant **lepton CP violation** could explain the observed density of matter in Universe with a **Leptogenesis Theory**.

- In order to verify or falsify specific symmetry approaches to lepton flavours and the various leptogenesis models with Dirac CP violation phase **δ_{CP}, this phase angle has to be measured with the highest possible precision.**

- Owing to the use of the world-uniquely high power of the ESS linear accelerator **the ESSnuSB project will enable a measurement of δ_{CP} with a standard error $\Delta\delta_{CP}$ below 8° for all values of δ_{CP}** to be compared with an error below 22° for all CP angles for DUNE and Hyper-K.



Other neutrino studies for which ESSnuSB will produce competitive results

Atmopsheric neutrinos: Neutrino mas hierarchy and mass ordering

Supernova neutrinos: Identify correct model for the supernova mechanism

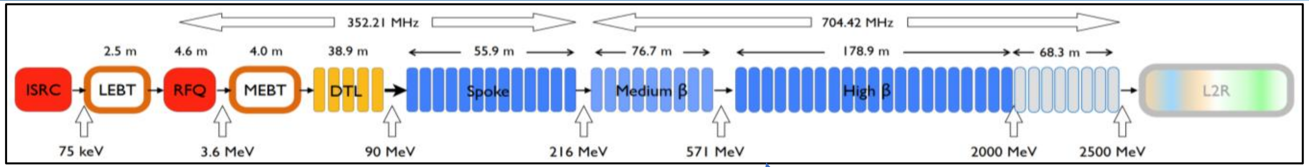
Solar neutrinos: Measure the solar neutrinos from the reaction $He^3 + p \rightarrow He^4 + e^+ + \nu_e$

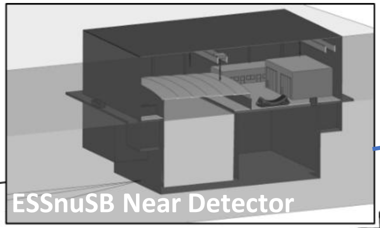
Invisible neutrino decay: Heavy neutrino state decays to a light sterile neutrino

Neutrino Scalar Non-Standard Interactions: Interaqctions mediated by a scalar field

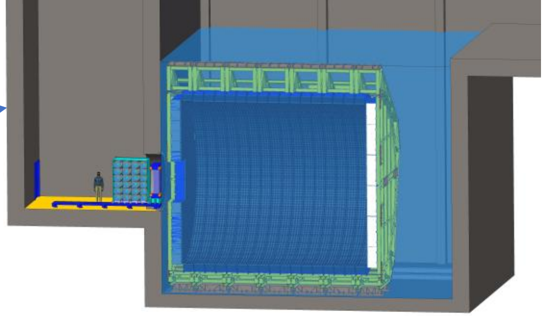
Neutrino Quantum Decoherence: Neutrino as a subsystem interacting with the environment giving rise to decoherence

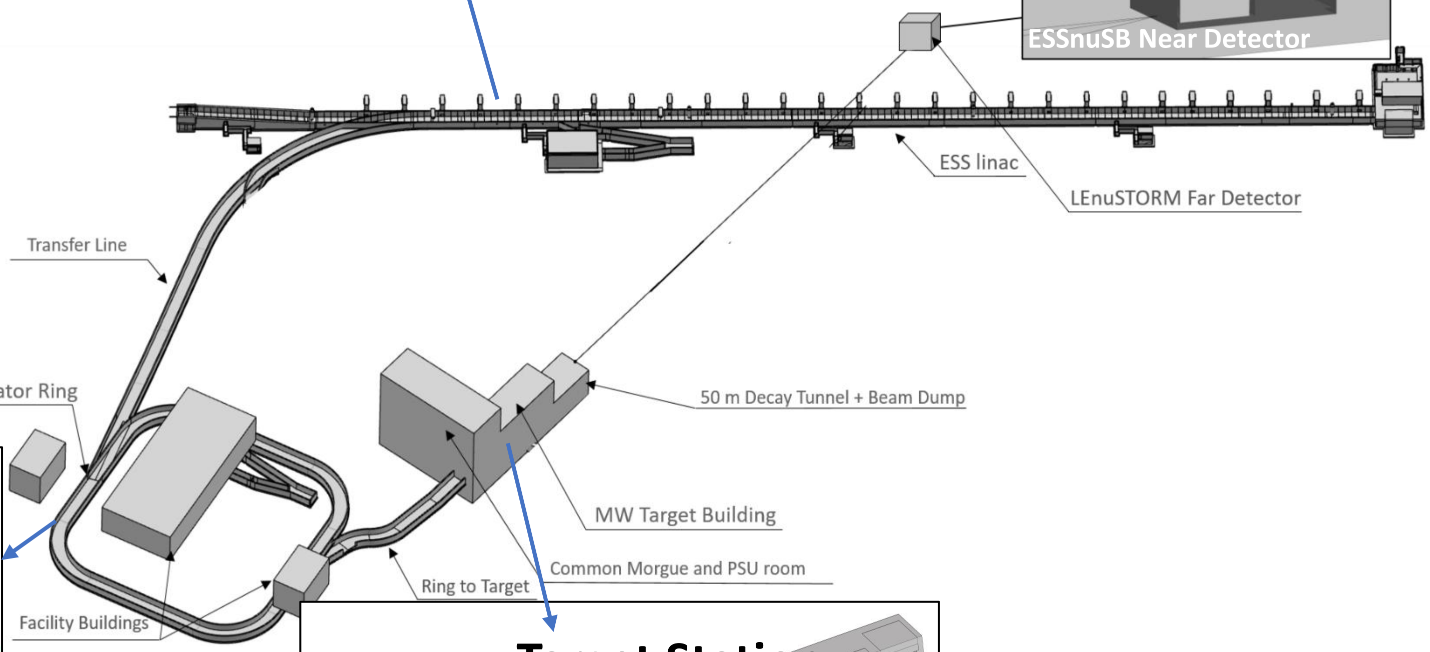
Ongoing design work: Adding LEMNB and nUSTORM to ESSνSB



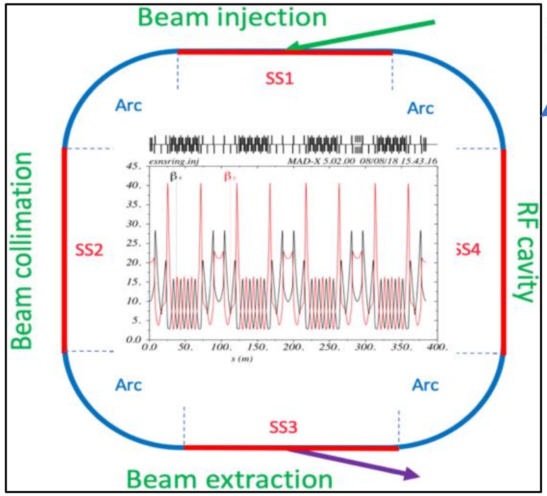


ESSnuSB Near Detector

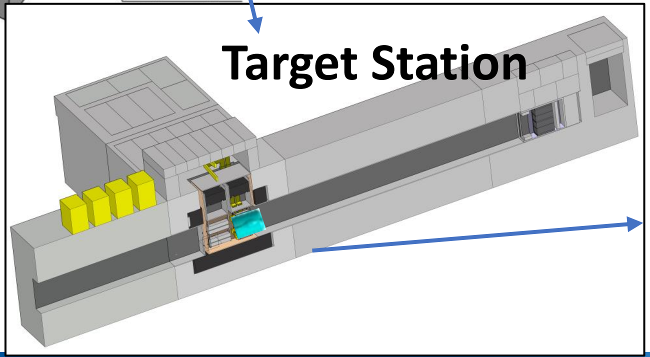


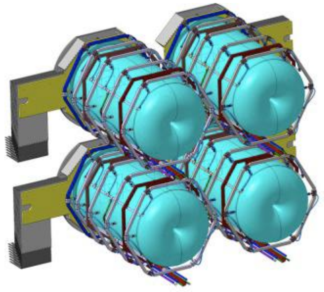


Accumulator Ring



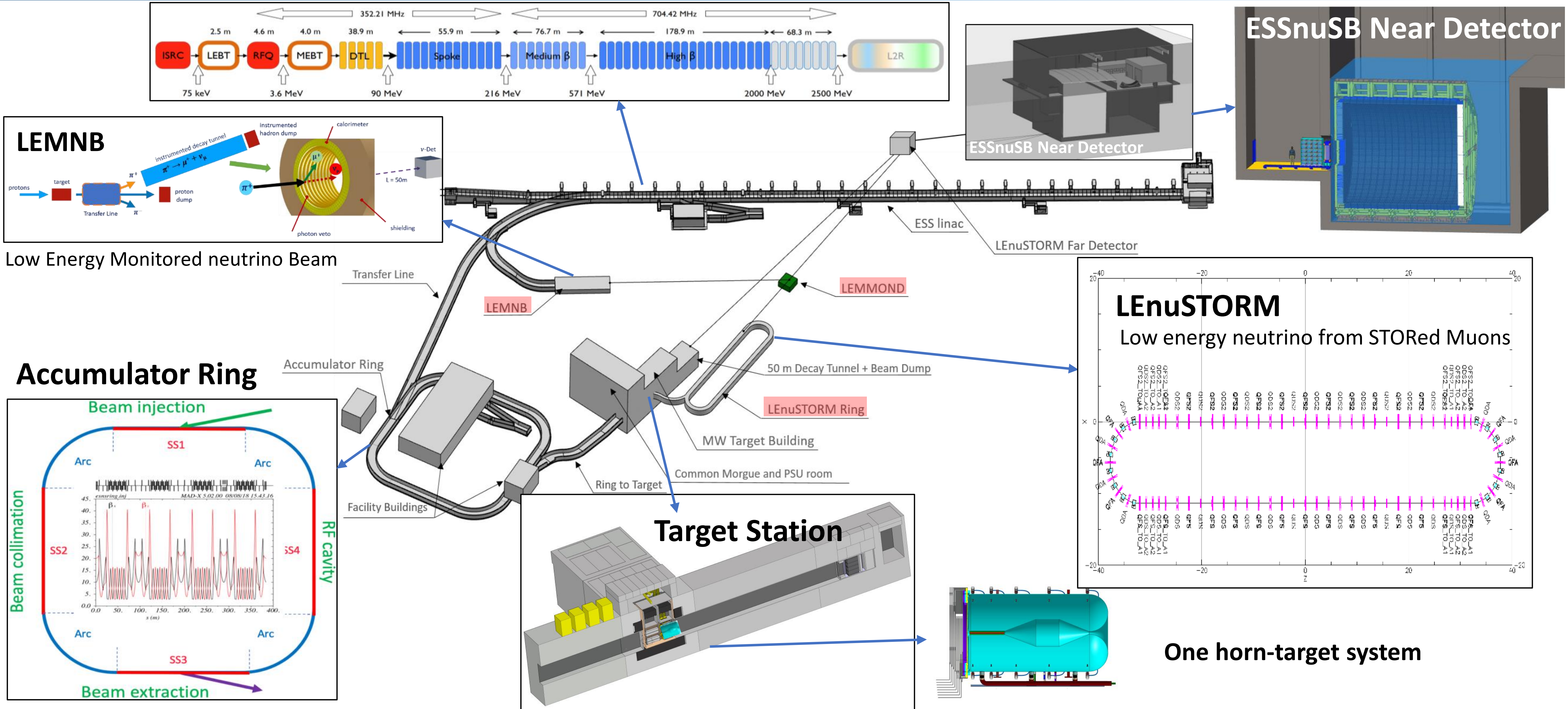
Target Station





Four horn-target system

Ongoing design work: Adding LEMNB and nuSTORM to ESSνSB



Next stage 2027-2030: Detailed design study of the Far Detector

Curren call: HORIZON-INFRA-2026-01-DEV-03 Consolidation of the Research Infrastructure landscape – Individual support for evolution, long term sustainability and emerging needs of pan-European research infrastructures

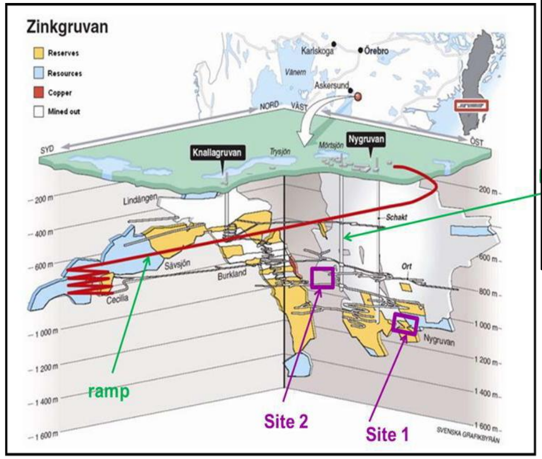
Title of Proposal: Design study of the ESSnuSB Far Detector infrastructure for fundamental neutrino oscillation research with additional benefits of their use for geological exploration and other uses

Acronym of Proposal: ESSnuSB-FD

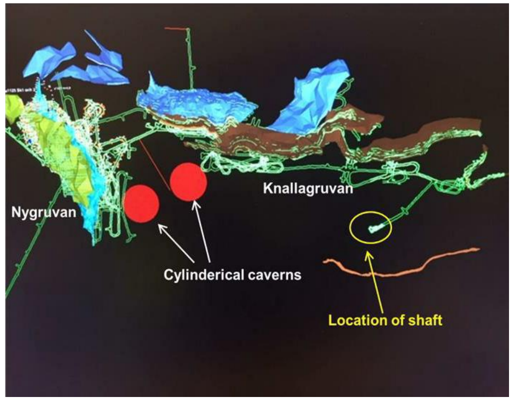
Coordinator: David Saiang, Luleå Technical University, Sweden

Zinkgruvan Mine Management support for ESSnuSB

Zinkgruvan Mining AB is a partner of ESSnuSB and its former Mine Manager Craig Griffiths attended the ESSnuSB+ Yearly Collaboration meeting at CERN in Oct 2023



Two potential sites identified are marked Site 1 and Site 2. Site 2 is considered as best considering access to main transport infrastructure and located in an area less disturbed by mining activities



Underground lay-out of Zinkgruvan Mine and photo from one of our visits there

Zinkgruvan Mine Manager Craig Griffiths (pointing upwards) visiting the Hyper-Kamiokande excavation site on 27 Sept 2023

Staged Implementation

Stage 1
LEMNB

- Proton beam from ESS linac, up to 2.86 ms pulses, long-pulses up to 10^{14} protons/pulse,
- ~300kW target station, pion capture using conventional magnets, instrumented decay tunnel
- Beam to near detector LEMMOND at ~40-50 m from the target

Stage 2
LENUSTORM

- H^- source, and transfer line to accumulator
- Accumulator ring, 1.25 MW target station, horn for pion capture, transfer line and injection to LEnuSTORM ring
- LENUSTORM ring, beam to near detector LEMMOND at ~10-15 m from ring, and to END at 290 m from target

Stage 3
ESSnuSB CPV LBL

- H^- source, and transfer line to accumulator
- Accumulator ring, 5MW target station, horn for pion capture
- Decay tunnel, beam to END at 290 m from target and FD

ESS neutrino Super Beam plus

Co-funded by the European Union

ESSnuSB Horizon-2020 (2018 - 2022), 3 M€
ESSnuSB+ Horizon-Europe (2023 - 2026), 3 M€

13 countries
23 Institutes

The European Spallation Source neutrino Super Beam plus (ESSnuSB+) collaboration

Conclusions

- A major goal of ESSnuSB is to **measure the lepton CP violation** with the highest possible precision and thereby to identify a theory **explaining the presence of matter in Universe**
- The first EU-supported (3M€ granted) phase of the ESSnuSB conceptual design study 2018-2021 has been successfully concluded with the publication of a ESSnuSB Conceptual Design Report, demonstrating the **feasibility of using the ESS 5 MW linac** as proton driver for a long base-line neutrino experiment with the **exceptionally high resolution of 8° in the CP violating phase angle δ_{CP}** .
- A second EU-supported (3 M€ granted) phase of the ESSnuSB design 2023-2026 is ongoing and is focussing on including facilities for **high precision neutrino cross-section measurements at low energy** needed for the CP angle phase measurement.
- A third phase of the ESSnuSB design study 2027-2030 has been proposed for EU funding (4 M€ requested) which shall focus on the **design of the Far Detector in Zinkgruvan**, its underground caverns, the clean water system, the photodetectors and data acquisition and analysis

- A design of the Accumulator ring for the generation om **medium length (~50-100 µs) spallation-neutron pulses for Material Science** is included in the third phase
- Discussions of how the transfer line from the ESS linac to the ESSnuSB Accumulator could be used also as transfer line also for a **high brightness neutron source optimized for very high pulsed magnetic field experiments** have started
- The ESSnuSB Collaboration, currently consisting of ca 90 members from 23 research institutions in 13 European countries, has had and has **strong support** from the EU Research INFRADEV Programme (Horison2020 and Horizon Europe), from the ESS Management and from the Zinkgruvan Mine Management.
- The plan is for the ESSnuSB to start construction around 2032 and **start data taking around 2040**.
- The ESSnuSB is an ESS-based neutrino super beam which **would add a new long-term vision to the ESS as a world-leading laboratory, also in Particle Physics**.