Outcome of the Design Study of the

ESS NEUTRINO SUPER BEAM

Presentation at NOW 2022 -09-06

J. Cederkall for the ESSnuSB collaboration

led by T. Ekelöf (Uppsala) & M. Dracos (Strasbourg)

Funded by the Horizon 2020 Framework Programme of the European Union

ESSnuSB Design Study ESSνSB January 2018 - March 2022

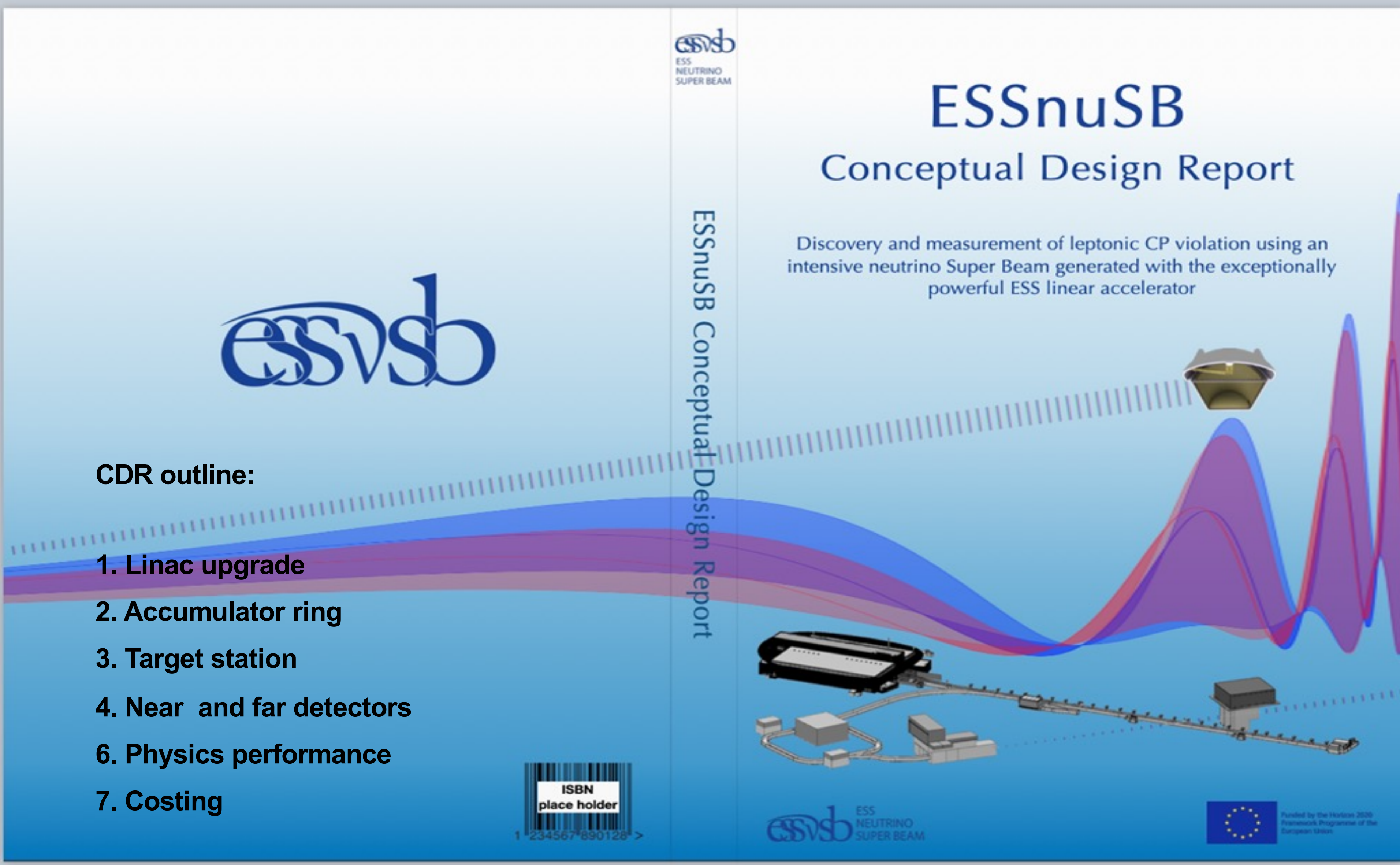
Call:	H2020-INFRADEV-2017-1
Funding scheme:	RIA
Proposal number:	777419
Proposal acronym:	ESSnuSB
Duration (months):	48
Proposal title:	Feasibility Study for employing the uniquely powerful ESS linear accelerator to generate an intense neutrino beam for leptonic CP violation discovery and measurement.
Activity:	INFRADEV-01-2017

N.	Proposer name	Country
1	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	FR
2	UPPSALA UNIVERSITET	SE
3	KUNGLIGA TEKNISKA HOEGSKOLAN	SE
4	EUROPEAN SPALLATION SOURCE ERIC	SE
5	UNIVERSITY OF CUKUROVA	TR
6	UNIVERSIDAD AUTONOMA DE MADRID	ES
7	NATIONAL CENTER FOR SCIENTIFIC RESEARCH "DEMOKRITOS"	EL
8	ISTITUTO NAZIONALE DI FISICA NUCLEARE	IT
9	RUDER BOSKOVIC INSTITUTE	HR
10	SOFIISKI UNIVERSITET SVETI KLIMENT OHRIDSKI	BG
11	LUNDS UNIVERSITET	SE
12	AKADEMIA GORNICZO-HUTNICZA IM. STANISLAWA STASZICA W KRAKOWIE	PL
13	EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH	CH
14	UNIVERSITE DE GENEVE	CH
15	UNIVERSITY OF DURHAM	UK
	Total:	

EU application
submitted in 2017
3 M€ granted for
the period 2018-2022

All results published
in an ESSnuSB CDR
On 6 June 2022

More information on the ESSnuSB site:
http://essnusb.eu/



CDR outline:

1. Linac upgrade
2. Accumulator ring
3. Target station
4. Near and far detectors
6. Physics performance
7. Costing

CDR published on arXiv 6 June 2022:
https://arxiv.org/abs/2206.01208
Accepted for publication in European Physical Journal ST

Schedule for a 2nd generation ESS-based neutrino Super Beam ESSnuSB

2012: Inception of the project

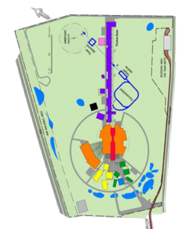
2016-2019: Beginning of COST Action EuroNuNet

2018: Beginning of ESSνSB Design Study (EU-H2020)

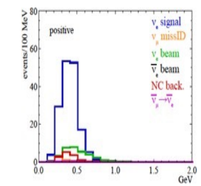
2022: End of ESSνSB Design Study, preliminary costing and CDR

2023-2026: Continuation of Design Study, final costing and an TDR to ESFRI

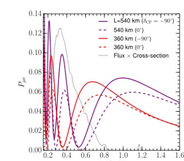
2027-2028: Preconstruction Phase, International Agreements



2029-2035: Construction of the facility and detectors, including commissioning



2036-: Start of data taking



Nucl. Phys. B 885 (2014) 127

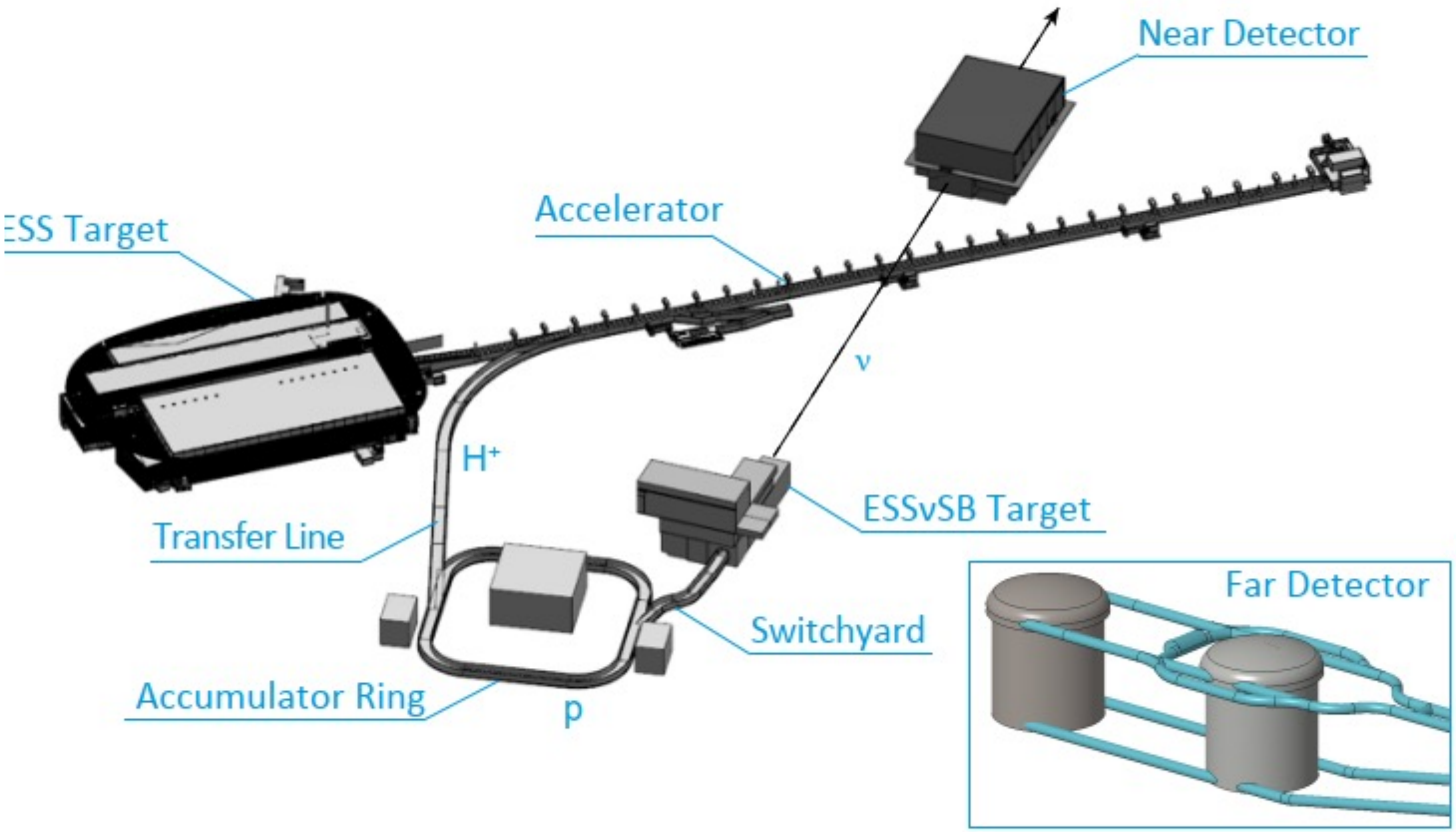

2019

Construction of the ESS buildings and landscape is completed

DECEMBER 22, 2021

Construction site overview: A seven-year-long civil construction project, where ESS and Skanska have worked in close collaboration, has now been successfully completed. Photo: Perry Nordeng/ESS.

ESSnuSB layout



The ESS linac

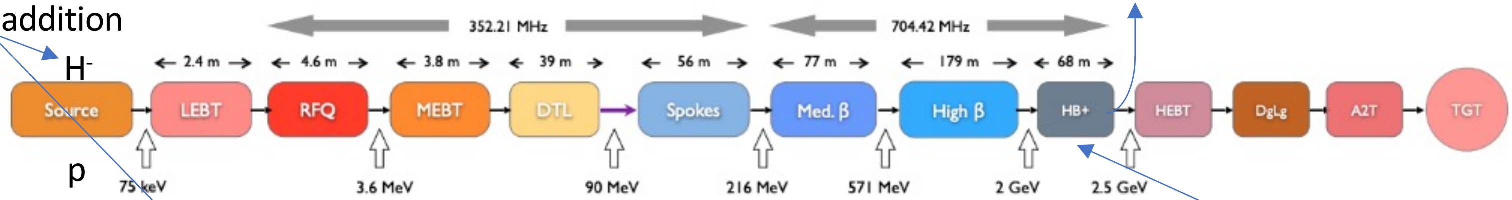
2.86 ms pulses at 14 Hz pulse frequency increase to 28 Hz, implying an increase of the beam power from 5 MW to 10 MW

Transfer Line to Accumulator

ESSnuSB addition

H^-

p

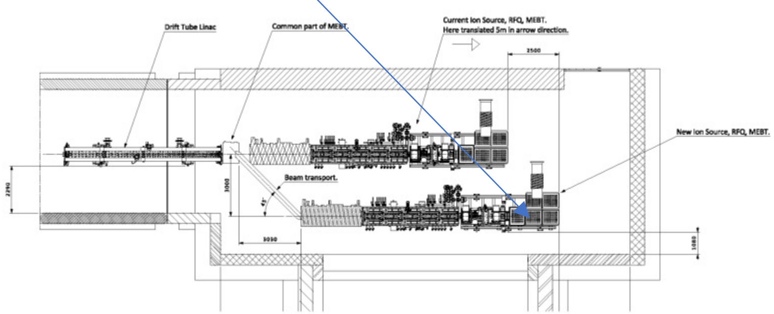


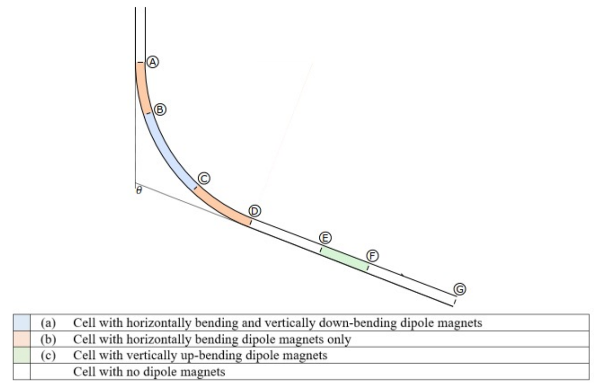
ESSnuSB addition

The linac

Normalconducting part

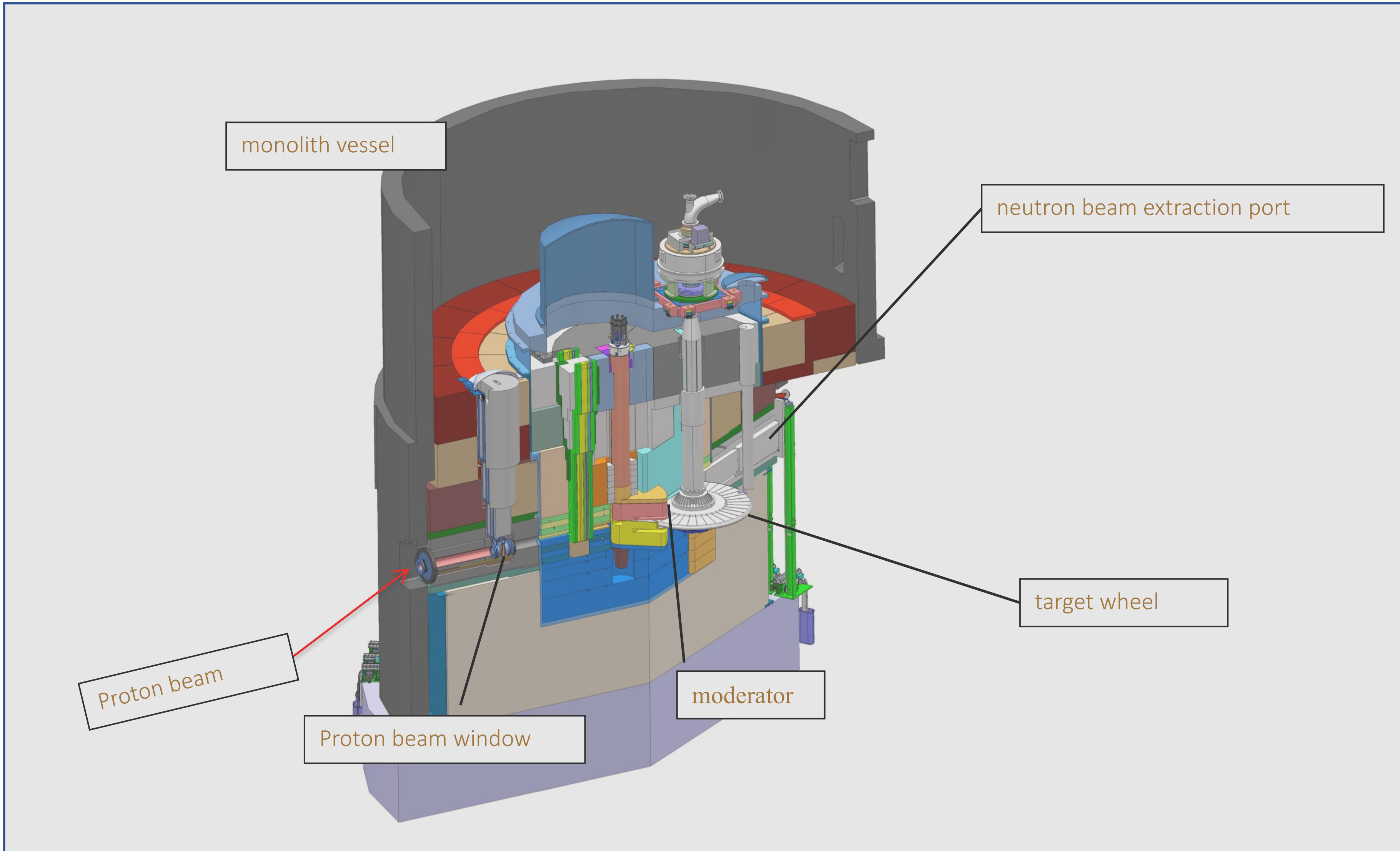
Superconducting part





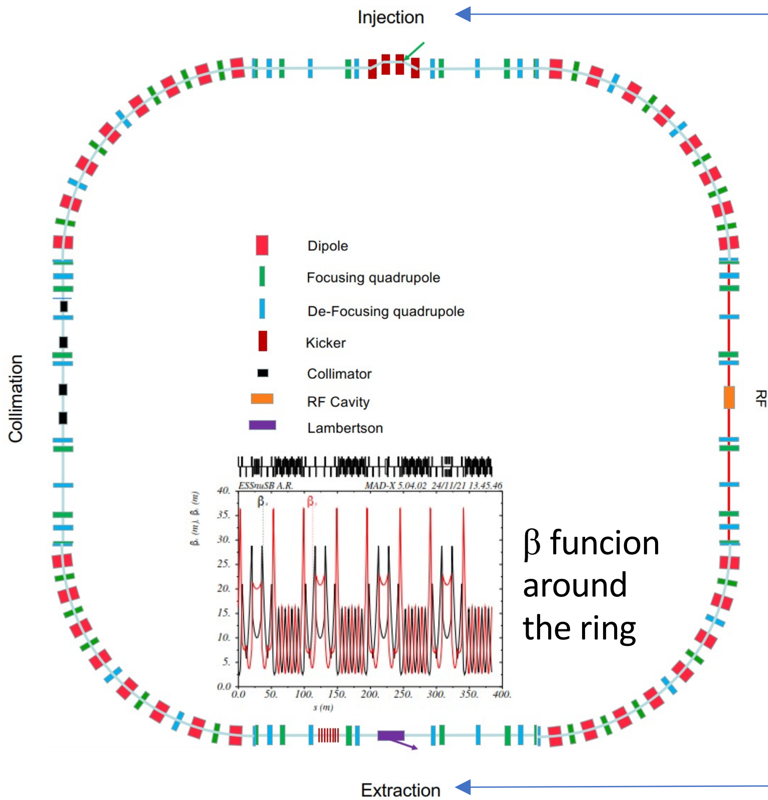
The merging of the H+ and the H- beams in the MEBT

The ESS target



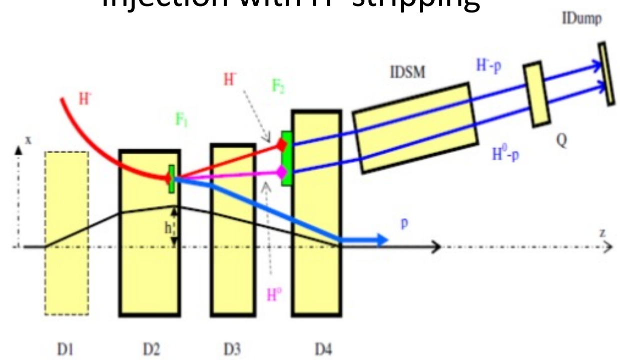
Linac tunnel and target building 2022

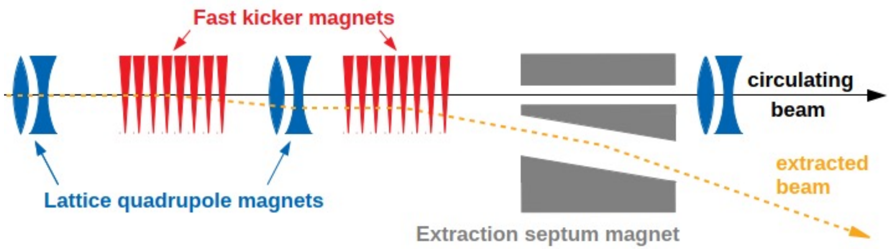
The Accmulator ring



β funcion around the ring

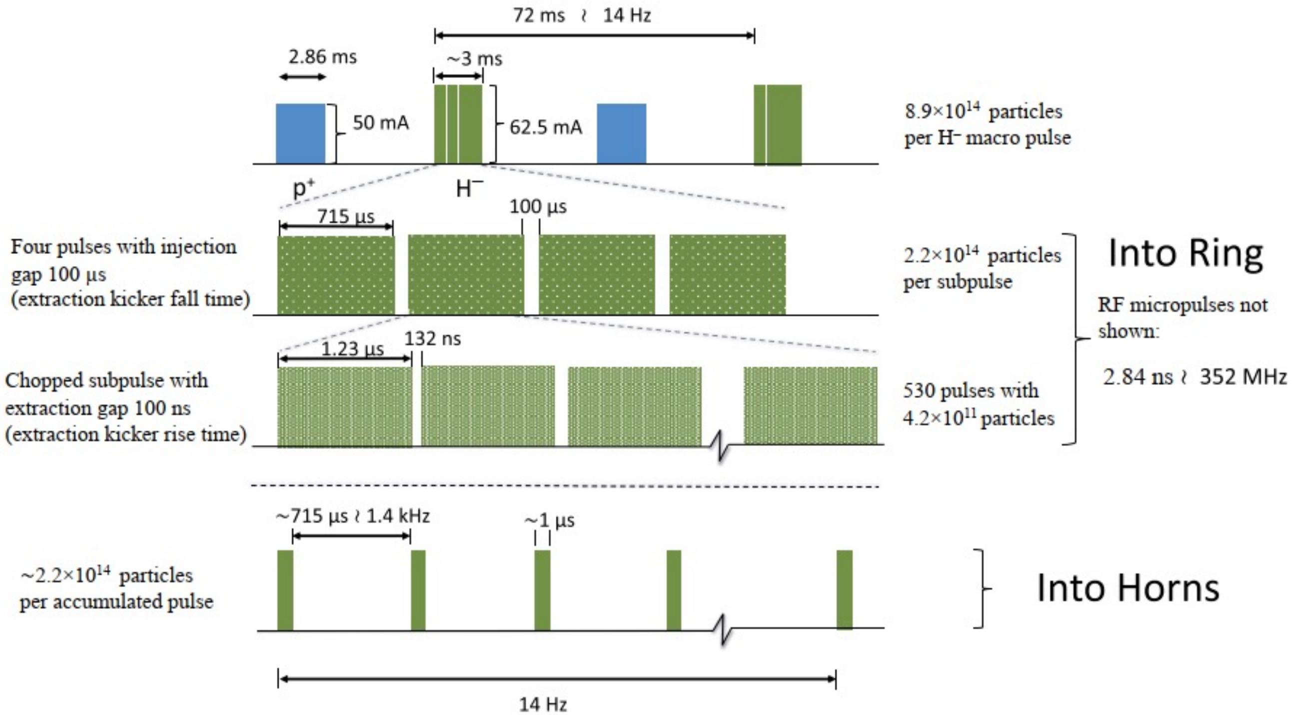
Injection with H- stripping



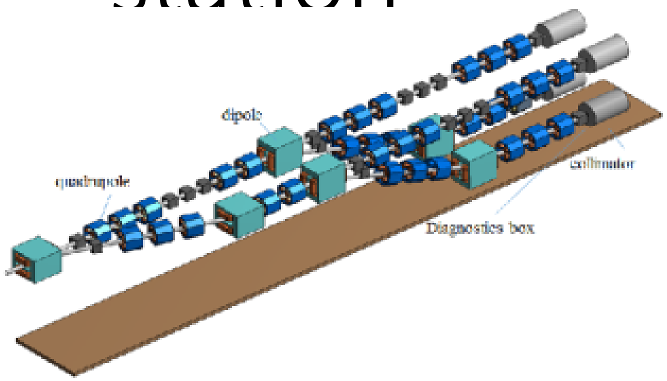


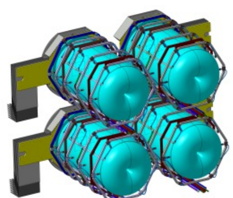
Extraction

Detailed schematic of the ESSvSB pulsing scheme

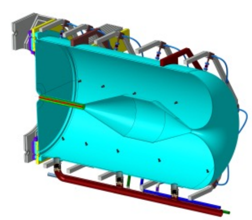


Beam switch-yard and the target station

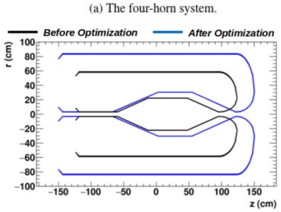




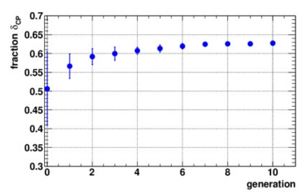
(a) The four-horn system.



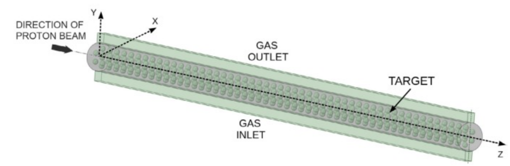
(b) Transverse view of one horn.

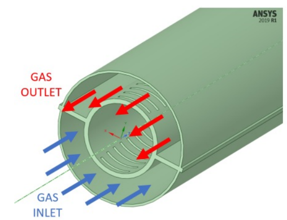


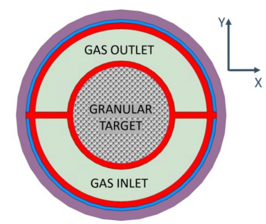
(a) Evolution of the horn profile.



(b) Genetic algorithm convergence throughout the iterative process.







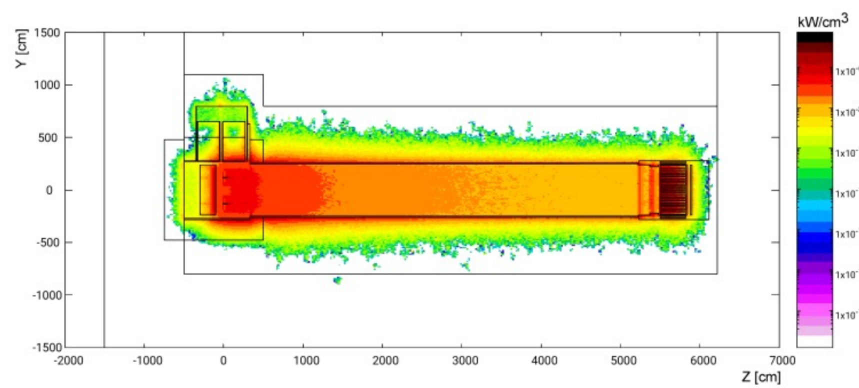
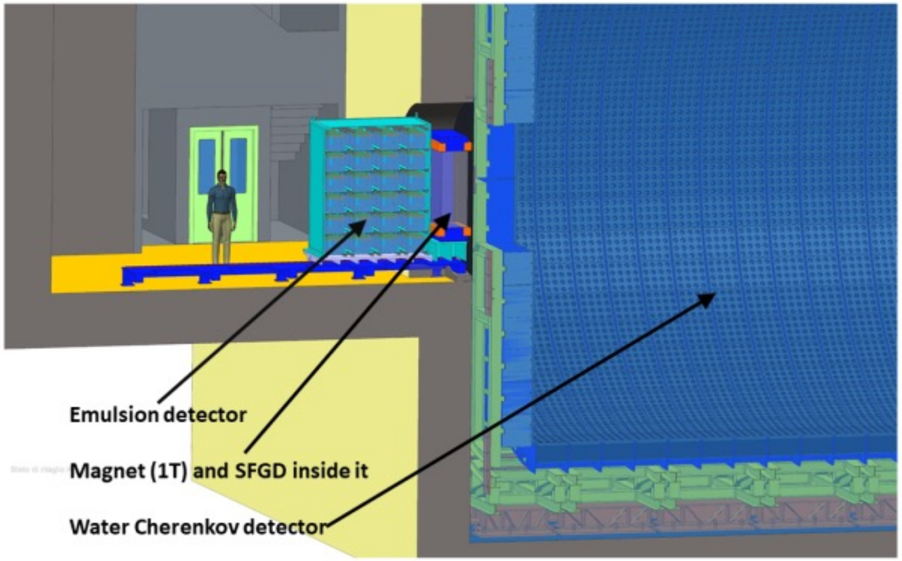
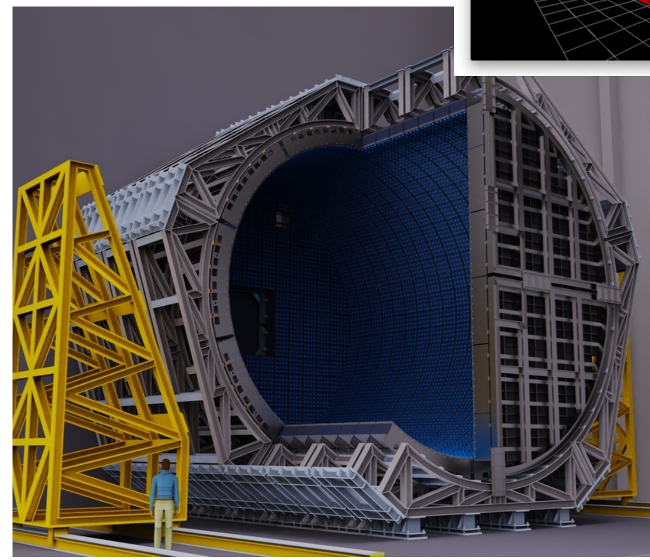
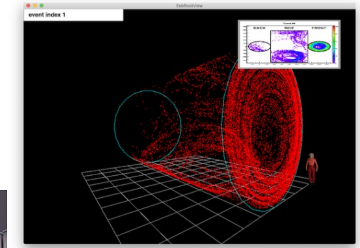


Figure 5.46: Energy deposition distribution in the target station facility.

The Near Detector







Near Detector underground station

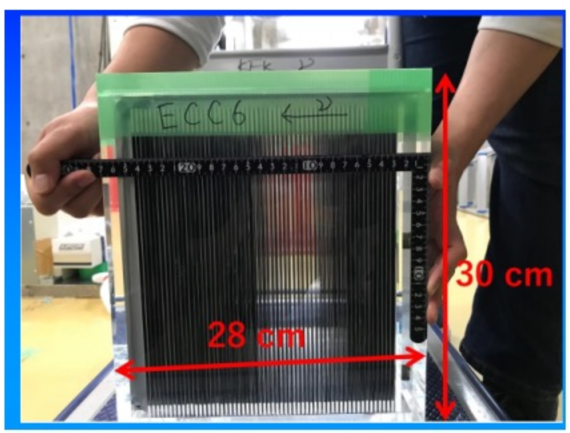
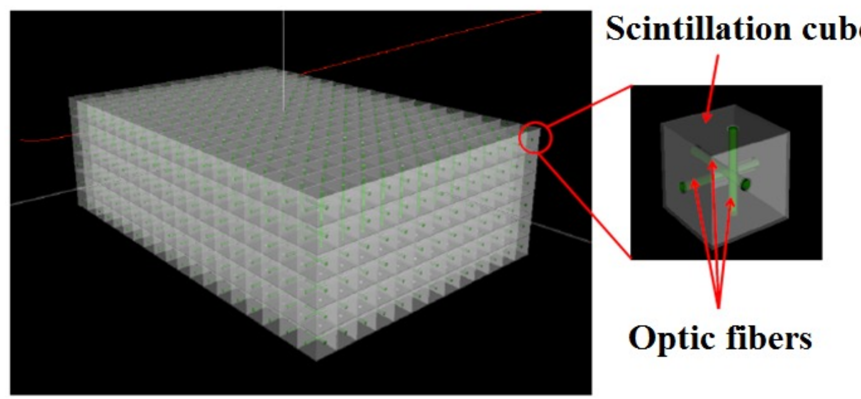


Figure 6.42: A photograph of the NINJA ECC element using water as target.



The super Fine-Grained Detector sFDG

The Far Detector

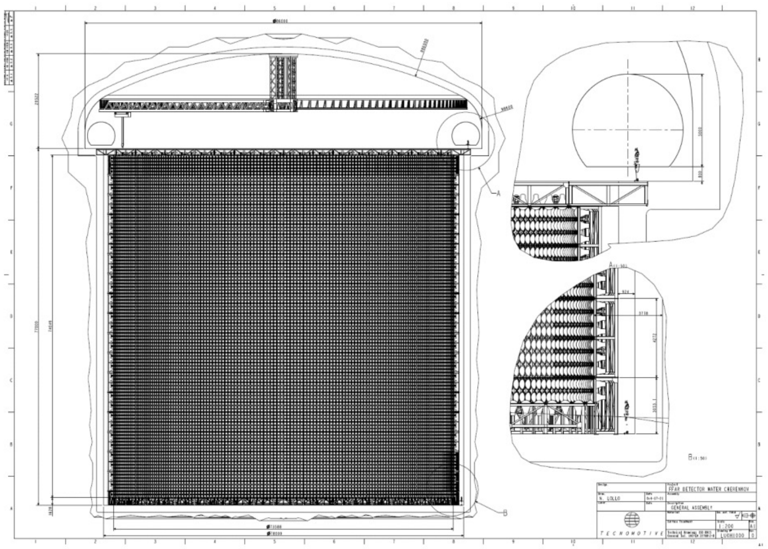
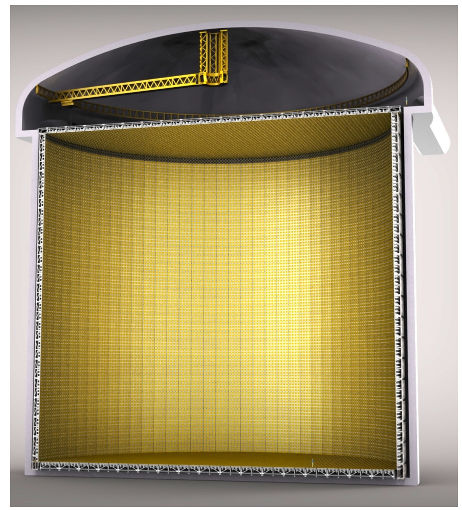
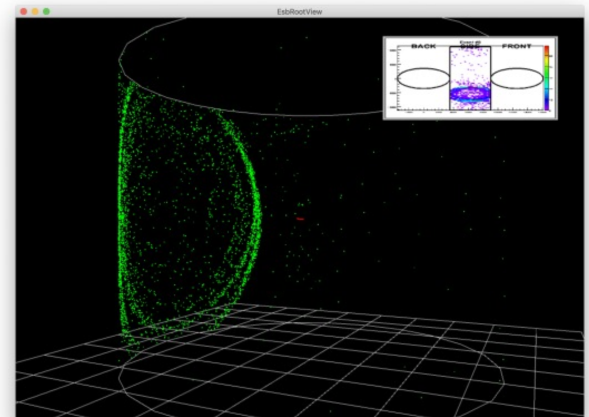


Figure 6.48: Overall view of a single far-detector tank with indicated dimensions.





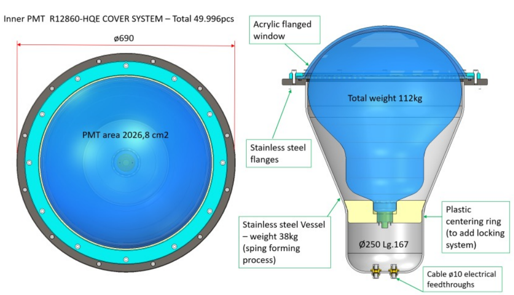
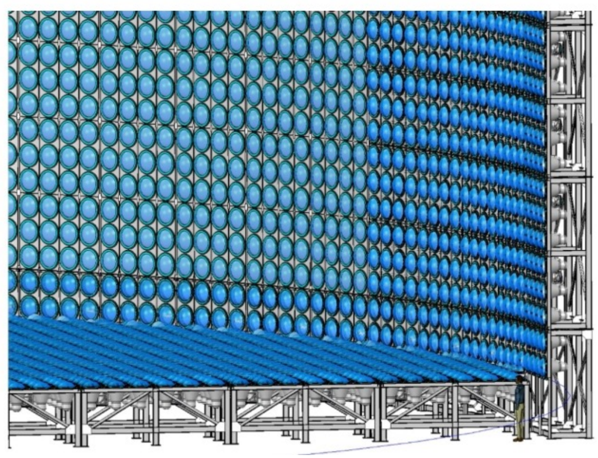


Figure 6.50: A schematic view of an inward-facing 20 inch PMT embedded in a protective cover.



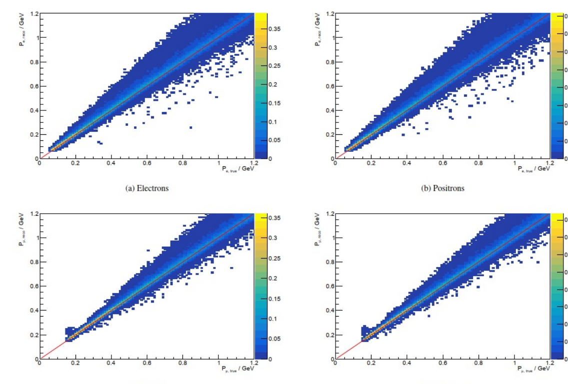


Figure 6.58: Distribution of reconstructed momentum as a function of true momentum for different flavours of charged leptons. These plots were produced using the charged lepton production.

7. Detectors

The principal objective of the ESSνSB project is to study the feasibility and design of a super-beam neutrino facility based on the European Spallation Source (ESS) proton linear accelerator to measure the CP-violating phase δ_{CP} in the lepton sector. The detector complex of the facility consists of a megaton-scale water Cherenkov (WC) far detector (FD) located at a distance of 360 km from the beam source and an efficient suite of near detectors (ND).

We note that previously published ESSνSB results have been directly included in this chapter.

7.1. Software Tools

Unless otherwise noted, the following software packages have been used in the analysis of the detector performance in this section:

GENIE The neutrino interaction vertex generator, GENIE v3.0.6 [204, 205, 206], was used to simulate neutrino vertices. The G18_10a_00_000 cross-section tune was used for this, and is shown in Fig.7.1 for neutrino interactions in water over an energy interval relevant for ESSνSB.

GEANT4 Particle propagation through the detectors and surrounding material was simulated by GEANT4 v10.4.1 [207, 208, 209]. It was not used directly, in favour of the dedicated simulation frameworks listed below (see ESBROOT and WCSIM below).

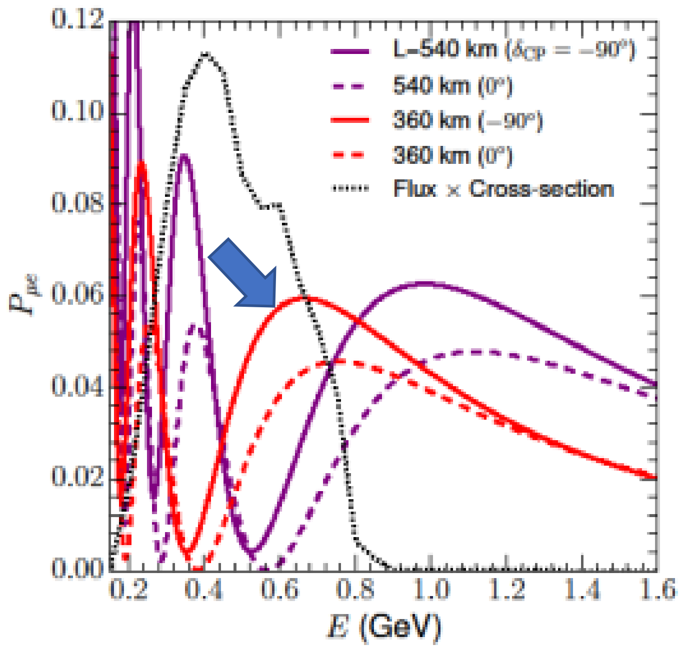
ESBROOT The simulation framework ESBROOT [210] has been developed in-house, based on FAIRROOT [211]. It was used directly for the simulation of the super-fine-grained detector (SFGD) detector and to set up the dependencies and environment for WCSIM and FITQUN.

WCSIM The water Cherenkov simulation software WCSIM [212] was used for particle transport post-vertex, and simulation of the detector response of both near and far WC detectors. WCSIM is based on GEANT4 and developed within the HYPER-KAMIOKANDE collaboration. The default version was modified for needs of this project.

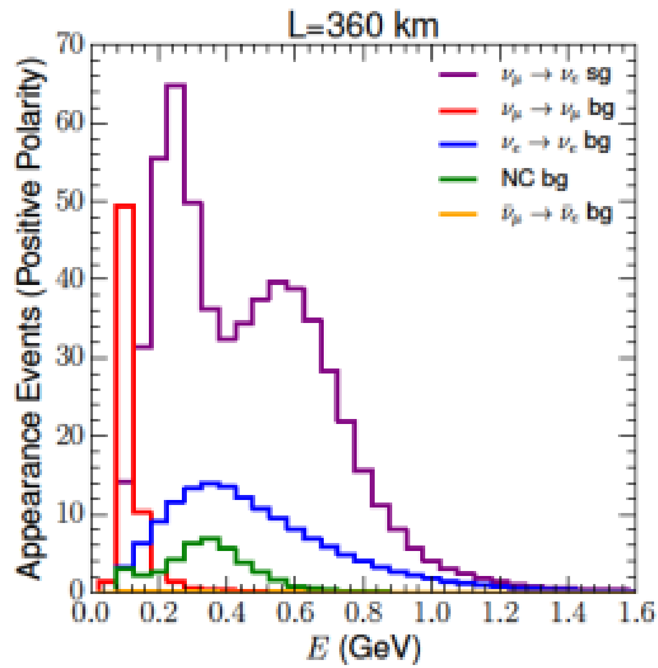
FITQUN The events simulated in WC detectors are reconstructed using the FITQUN software [213, 214], also native to the HYPER-KAMIOKANDE collaboration. FITQUN fits the detector response to several particle hypotheses, including variations in, for example, particle flavor, vertex position, particle direction and momentum, as well as in the number of registered sub-events (estimating the number of final-state visible particles in the interaction). The default version was modified for needs of this project.

ESBROOTVIEW A versatile event viewer for the EsbRoot data model developed in-house [215]. It allows visualisation of simulated events both as still and animated scenes. Seamlessly works on multiple platforms including handheld devices and web browsers.

ESSnuSB at the second neutrino oscillation maximum

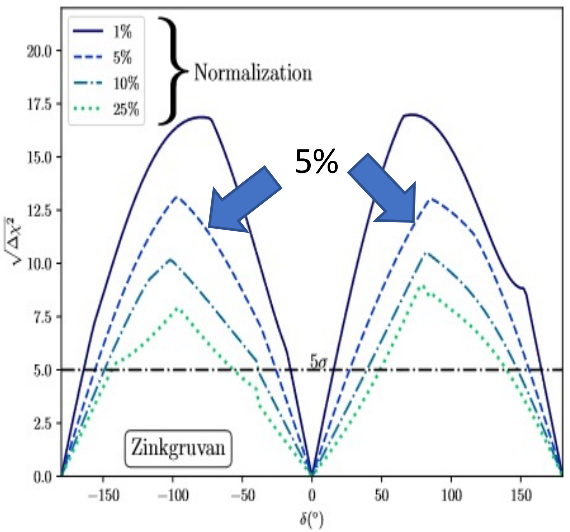


Coverage of the second oscillation maximum

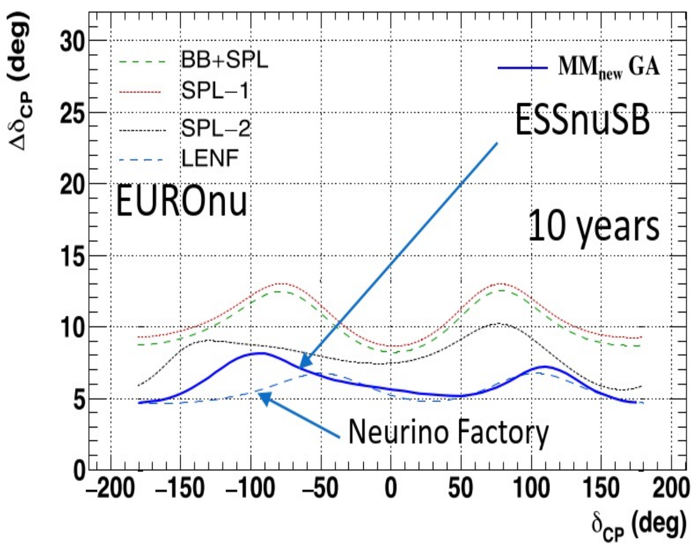


Signal (ν_e) and background energy distributions

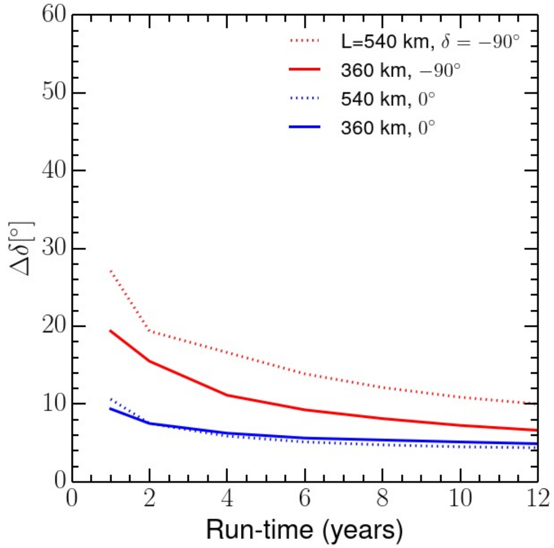
Performance for CPV discovery and δ_{CP} measurement



Discovery potential vs δ_{CP} angle after 10 years with 5% normalization error providing 70% coverage of all δ_{CP} vaues

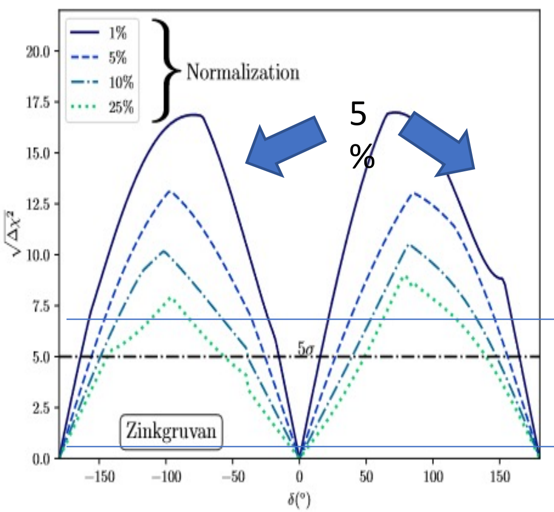


Error in δ_{CP} angle vs δ_{CP} angle after 10 years with 5% normalization error

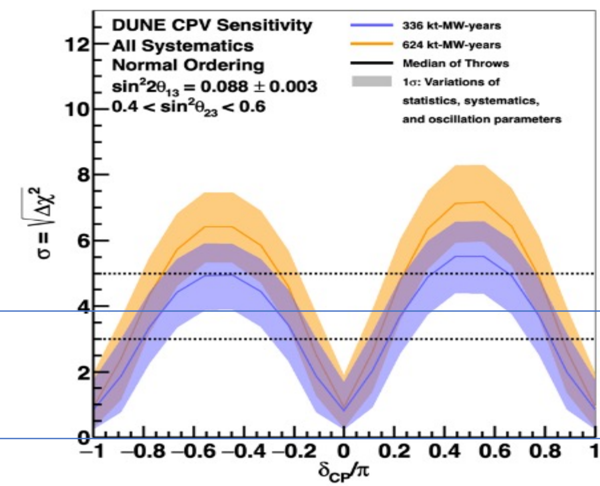


Error in δ_{CP} angle vs run time with 5% normalization error

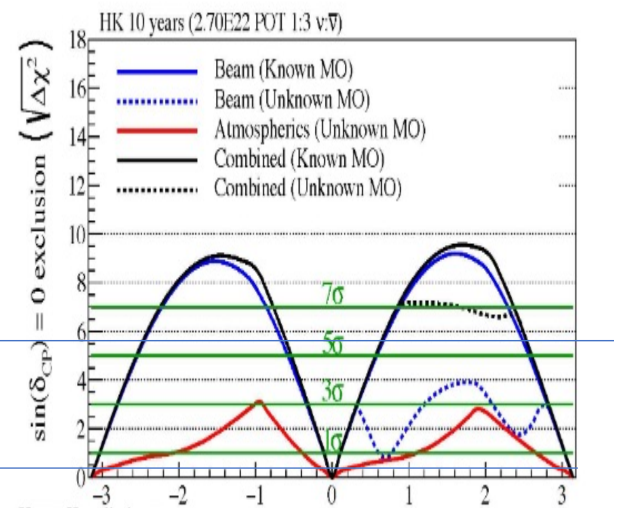
ESSnuSB in the international context – CPV discovery



ESSnuSB March 2022 with 5% normalization error

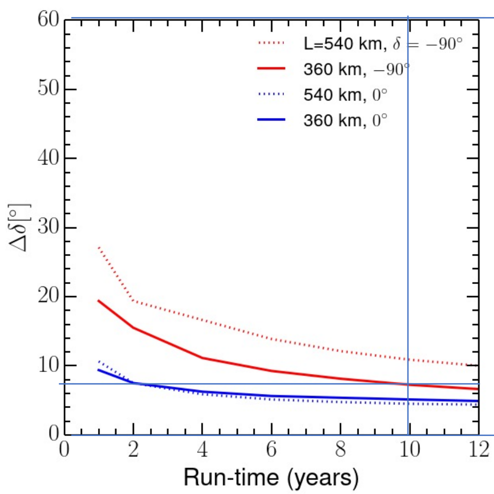


DUNE Snowmass March 2022

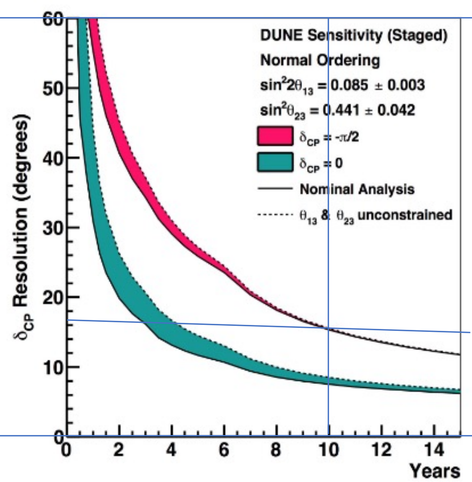


HyperKamiokande Snowmass March 2022

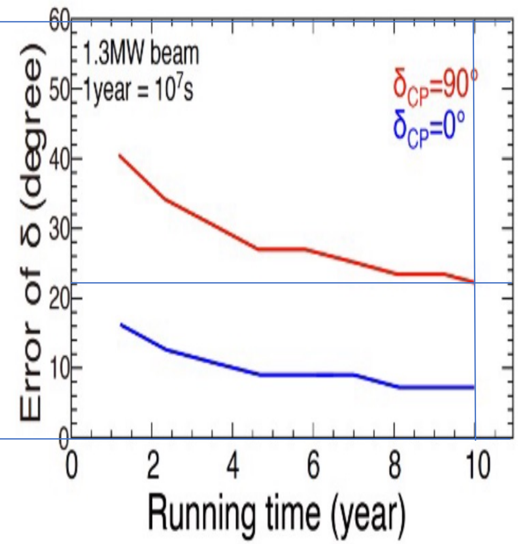
ESSnuSB in the international context – CPV resolution



ESSnuSB March 2022 with 5% normalization error

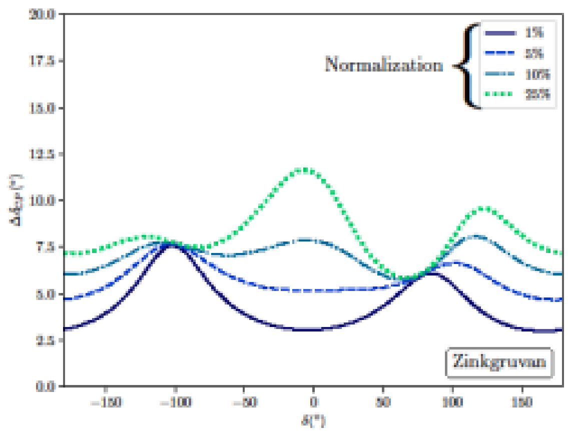


DUNE Snomass March 2022

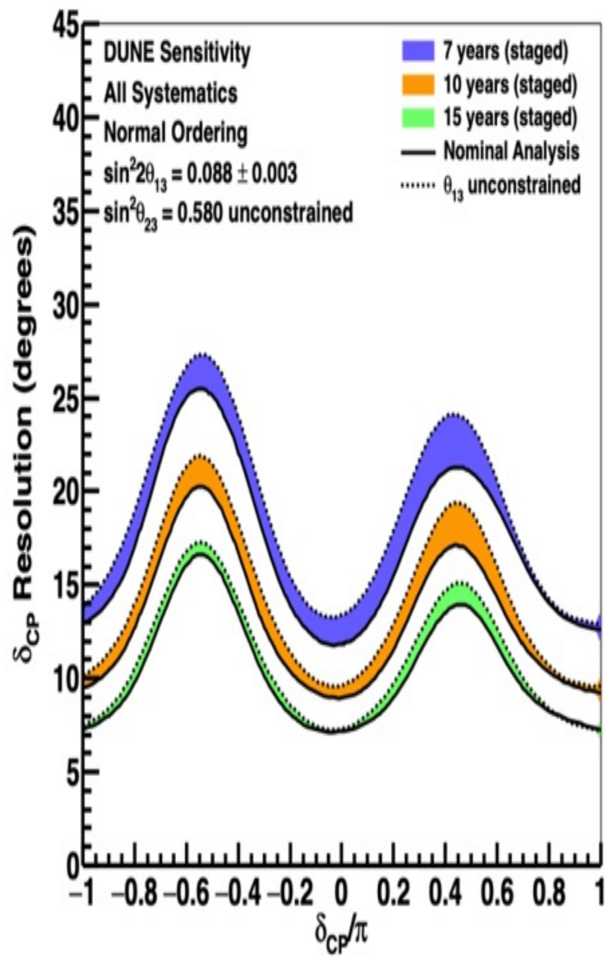


HyperKamokandeSnowmass March 2022

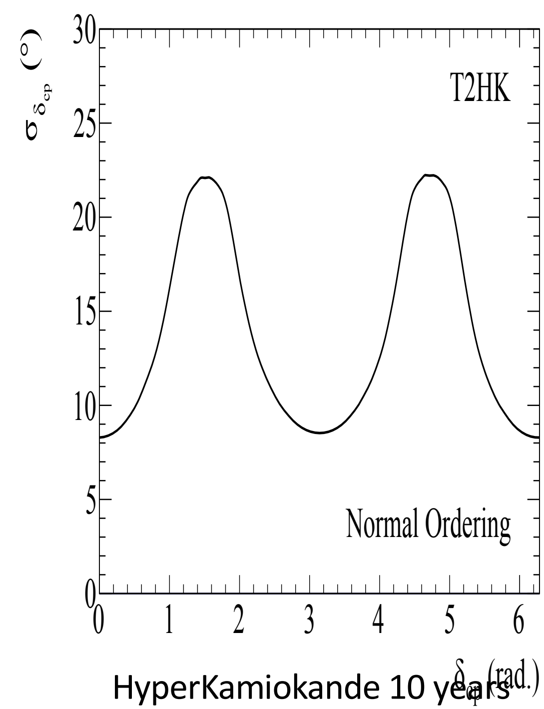
ESSnuSB in the international context – precision in δ_{CP}



ESSnuSB 10 years



DUNE 10 years yellow curve



HyperKamiokande 10 years

ESSnuSB Cost Esimate

1’382 M€

The cost of civil engineering on the ESS site is not included.

A cost estimate of the civil engineering will require a detailed study of the implementation of the components on the ESS site, that will be made only in the next phase of the study.

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%**

ESSnuSB support letters from 4 ESS Director Generals:

Jim Yeck in 2014

EUROPEAN SPALLATION SOURCE

Date: 19 May 2014

To the European Commission's Horizon 2020 Research Infrastructure Office

Subject: Support for the ESSnuSB Conceptual Study

ESS notes that the ESSnuSB collaboration is planning a Design Study of ways to increase the average power of the ESS linear accelerator from 5 MW to 10 MW by doubling the duty cycle from 4% to 8%. This collaboration includes an international group of scientists and engineers from a number of research institutions including the universities of Durham, Krakow, Lund, Madrid, Sofia, Stockholm-KTH, Strasbourg and Uppsala and the laboratories of CERN, ESS, Fermilab and RAL. The goal of the collaboration is to determine the best way to produce the highest flux neutrino-beam in the world. An important boundary condition for the conceptual study, according to the ESSnuSB group, is that the ESS mission for neutron production will not be compromised in any way. An additional ESS boundary condition is that any ESS engagement in the study will not divert our staff from their current priorities, i.e., successful delivery of the ESS baseline linear accelerator.

The stated scientific aim of the Design Study is to specify how the high flux neutrino beam would be produced and how the beam would make possible the discovery of CP violation in the neutrino sector. According to the ESSnuSB group, this scientific goal could be achieved by comparing the rates of appearance of electron neutrinos and electron anti-neutrinos at the second neutrino oscillation maximum. The second maximum for the enhanced ESS parameters is approximately 500 km from the ESS site. My understanding is that at this distance there is an appropriate underground location for a large neutrino detector available. New neutrino measurements, published in 2012, imply that the CP violation signal at the second maximum is significantly larger than at the first maximum. Other planned neutrino experiments in the US and Japan, proposed before 2012, is designed to measure neutrino oscillations at the first maximum and will not have access to the second maximum. Statistically significant measurements at the second, more distantly situated maximum would be made possible only by the use of the exceptionally high proton beam flux of the ESS linear accelerator.

Given the high scientific interest in exploring the possibility of using the future ESS linear accelerator for neutrino physics, interesting additional user communities, and a shared commitment to the above mentioned boundary conditions for the Design Study, ESS management agrees to provide information and general support for the ESSnuSB collaboration's ongoing studies.

James Yeck
Director General and CEO

European Spallation Source ESS AB
Visiting address: ESS, Tunavägen 24
P.O. Box 176
SE-221 00 Lund
SWEDEN
www.esss.se

John Womersley in 2017

EUROPEAN SPALLATION SOURCE

To whom it may concern – ESSnuSB project

The European Spallation Source (ESS) is now well into its construction phase and all indications are positive. The ESS is naturally concentrating on delivering first neutrons and achieving full specification such that we can deliver the transformational science that such a powerful source will enable. This is our top priority. At the same time we are aware of the future potential of the ESS laboratory. There are a number of future pathways and among them is the possibility, being explored by the very imaginative ESSnuSB project to deliver high intensity beams of neutrinos. Neutrinos offer a window to the fundamental structure of the universe which is totally independent and complementary to high energy colliders such as CERN. The ESSnuSB project is coming together around an increasingly credible science case and has assembled a strong international scientific collaboration with members from 12 European countries now organized as a EU COST Association, of which ESS is an associate member.

The ESSnuSB collaboration is currently studying how the average power of the ESS linear accelerator could eventually be increased from 5 MW to 10 MW by doubling the duty cycle from 4% to 8% with the goal of producing the highest flux neutrino-beam in the world. The primary scientific aim of the study is to specify how such a high flux neutrino beam would be produced and explore what new ground breaking neutrino physics would then become possible. The discovery of matter-antimatter asymmetries in the neutrino sector is especially tantalizing, as it could explain the observed preponderance of matter over antimatter in our universe. The exceptionally high power possible in an eventual ESS neutrino beam would allow for the neutrino measurements to be made at the second neutrino oscillation maximum, where the CP signal is three times larger than at the first maximum. This provides a clear advantage over the current generation of neutrino projects planned in US and Japan, respectively. The ESSnuSB project also opens up the possibility, at a future stage, of making use of the intense flux of muons generated concurrently with the neutrinos and to enable the generation of high-brightness short-pulse neutron beams.

It is now important for the ESSnuSB project to embark upon a sustained design phase so that its feasibility can be properly judged when the time comes. For the reasons given above I have no hesitation in fully endorsing the application for INFRADEV support so that a professional Design Report and an outline costing can be available by 2020 when ESS will be operational and its future development pathways can be assessed.

Lund, February 13, 2017

John Womersley
Director General

European Spallation Source ERIC
Visiting address: ESS, Tunavägen 24
P.O. Box 176
SWEDEN

Kevin Jones in 2021

EUROPEAN SPALLATION SOURCE

Lund, May 25th 2021

Dear Tord,

I was very pleased to hear of the progress that you have made with the ESSnuSB design study and I look forward to reading the Conceptual Design Report (CDR) in due course. The second phase of your work is very innovative and deserves to be supported. It broadens considerably the scientific scope and impact of the proposed upgrade to the ESS linear accelerator (linac). I encourage you to put the considerable energies and expertise of your collaboration into this second phase.

On behalf of the ESS organisation I would like to reiterate our continued strong support for the neutrino and muon physics opportunities presented by the ESSnuSB initiative as previously communicated by John Womersley in 2017.

Please keep me posted on the outcome of the upcoming TIARA meeting and your further progress.

With best regards

Kevin Jones
Acting Director General

European Spallation Source ERIC
Visiting address: ESS, Odarslövsvägen 113
P.O. Box 176
SE-221 00 Lund
SWEDEN
www.ess.eu

Helmut Schober in 2022

EUROPEAN SPALLATION SOURCE

Lund, March 23, 2022

Dear Tord,

I was very pleased to hear of the progress that you have made with the ESSnuSB design study and I look forward to reading the Conceptual Design Report (CDR) in due course. The next phase of your work ESSnuSB+ is very innovative and deserves to be supported. It consolidates and broadens considerably the scientific scope and impact of the proposed upgrade to the ESS linear accelerator (linac). I encourage you to put the considerable energies and expertise of your collaboration into this second phase.

While concentrating all our efforts on realising the current baseline, I would like to reiterate ESS's continued strong support for exploring the use of neutrinos and muons at ESS to create the new physics opportunities presented by the ESSnuSB initiative as previously communicated by ESS Director General in 2017 and 2021.

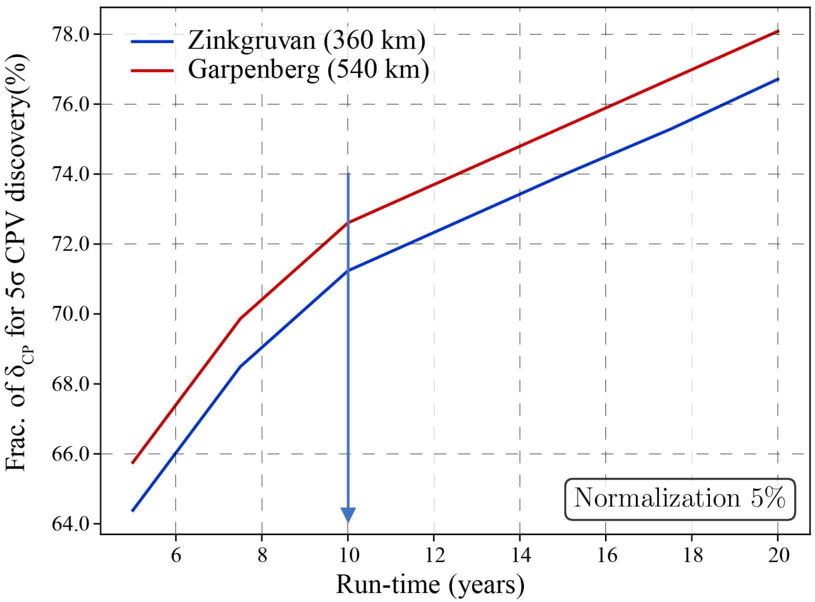
Please keep me posted on your further progress.

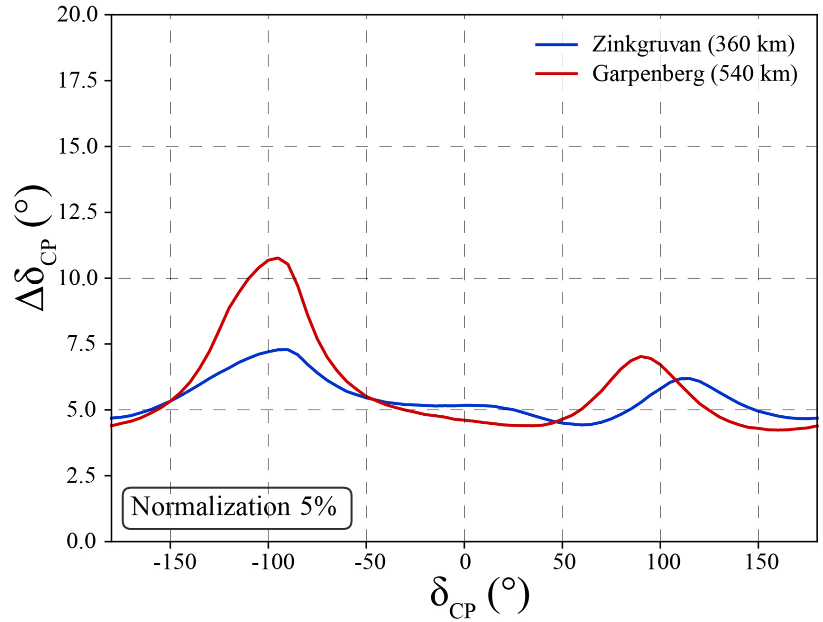
With best regards

Helmut Schober
Director General

Helmut Schober: "I would like to reiterate ESS's continued strong support for exploring the use of neutrinos and muopns at ESS to create the new physics opportunities by the ESSnuSB initiative as previousely communicated by ESS Director Generals in 2014- 2021."

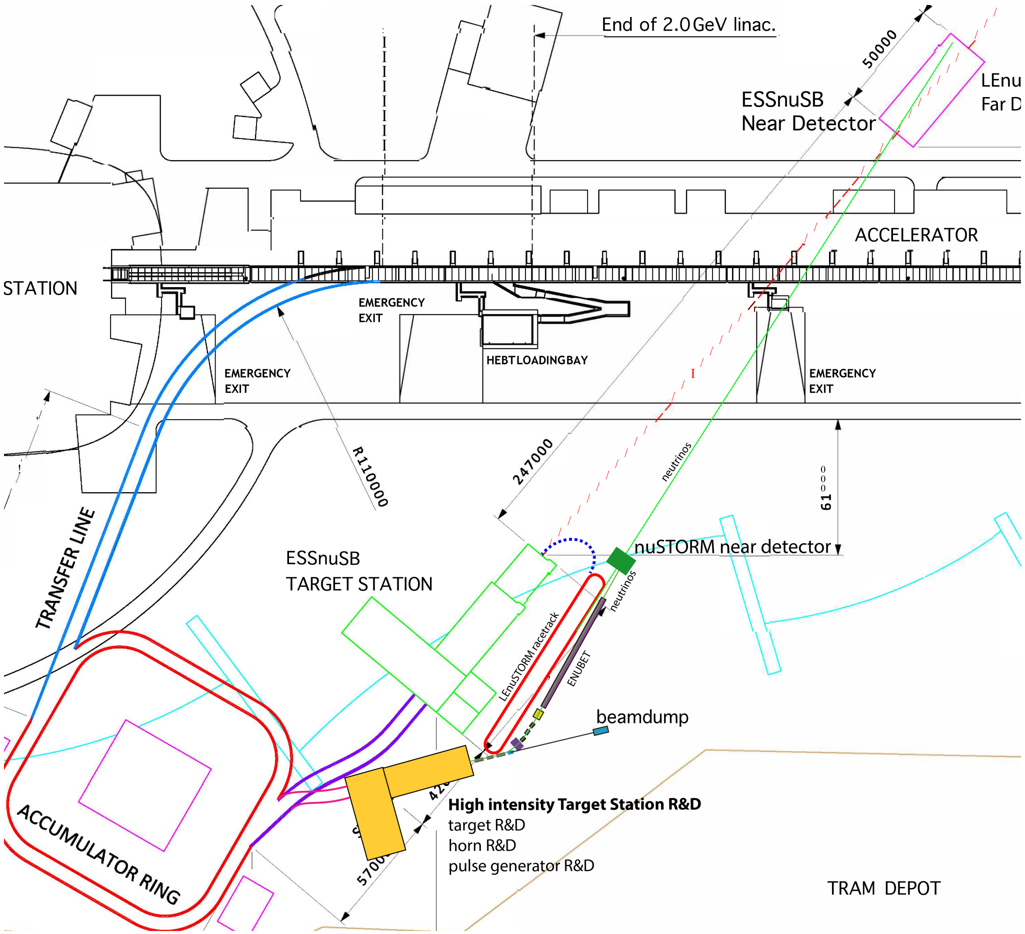
ESSnuSB to ESSnuSB+





The ESSνSB Consortium has produced a comprehensive Conceptual Design Report (CDR) of the complete ESSνSB neutrino facility proving the feasibility of all proposed elements. In this CDR, it is demonstrated that the initially foreseen physics performance has surpassed all earlier expectations by covering after 10 years of data collection more than 70% of δ_{CP} with a confidence level of more than 5 σ to reject the no-CPV hypothesis. The expected measurement precision of the value of δ_{CP} is better than 8° for all δ_{CP} values, making it the most precise proposed experiment by a large margin.

Upcoming studies



Cross-section measurements with:

- Low Energy nuSTORM: $\pi \longrightarrow \mu \longrightarrow e+\nu_\mu+\nu_e$
- Low Energy ENUBET: $\pi \longrightarrow \mu+\nu_\mu$

1. **Design of a racetrack storage** ring for low energy muons produced with a beam from the ESS linac.
2. Design a transfer system from the initial **collection and extraction of pions** behind the target station, up to the injection point.
3. Design a **transfer line** from the ESSνSB ring-to-switchyard transfer line to the **nuSTORM target**.
4. Design an **injection scheme** for the racetrack storage ring
5. Design a **Monitored Neutrino Beam** (low energy ENUBET)
6. **Optimize the performance** of the ESSνSB accelerator complex

Thank you