Outcome of the ESSνSB Design Study 2018-2022

A report at the NuFact2022 Workshop on
the achievements of the ESSνSB Design Study 2018-2022

Funded by the Horizon 2020 Framework Programme of the European Union

ESSnuSB Design Study ESSνSB January 2018 - March 2022

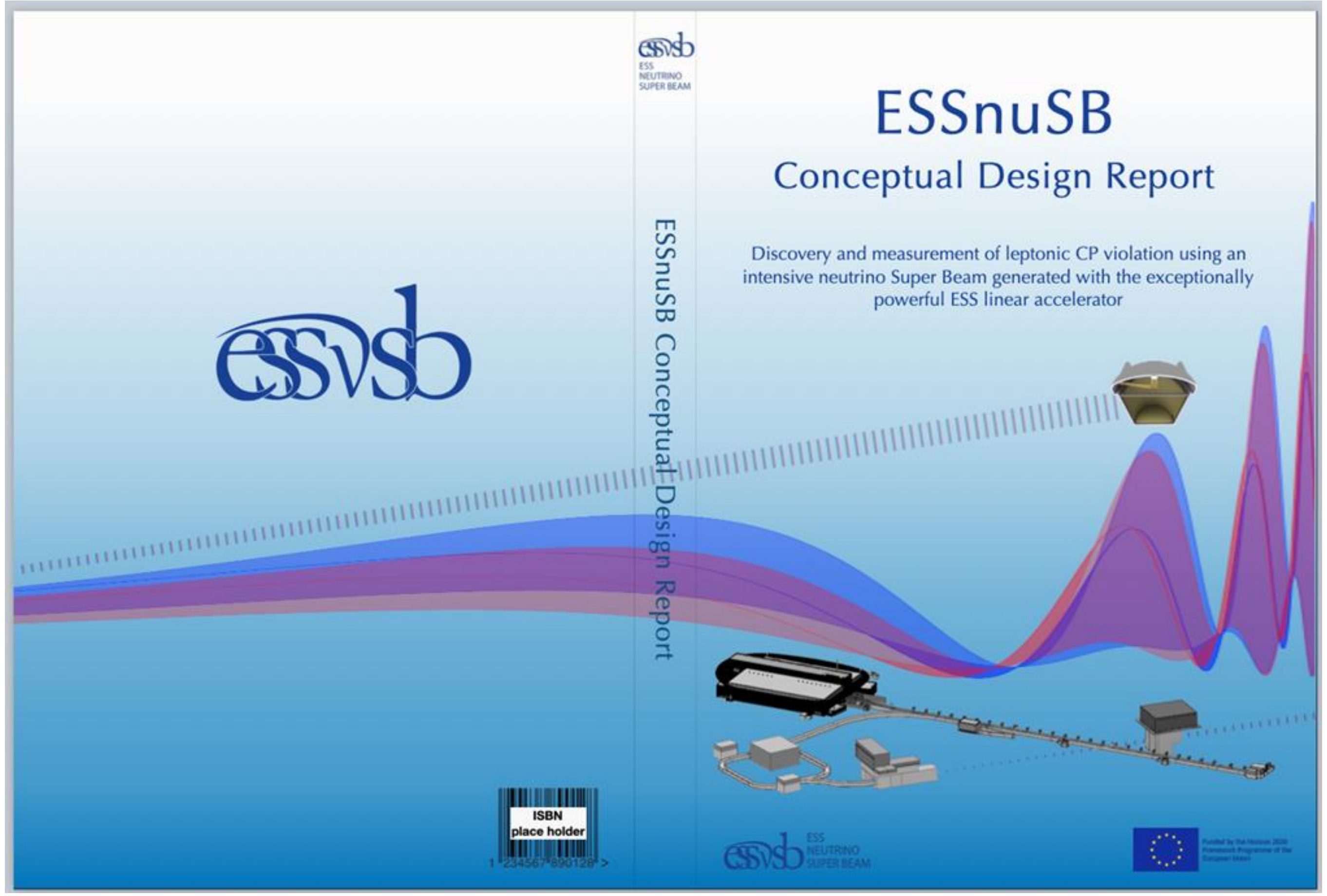
Call:	H2020-INFRADEV-2017-1
Funding scheme:	RIA
Proposal number:	777419
Proposal acronym:	ESSnuSB
Duration (months):	48
Proposal title:	Feasibility Study for employing the uniquely powerful ESS linear accelerator to generate an intense neutrino beam for leptonic CP violation discovery and measurement.
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 published on arXive 6 June 2022:
https://arxiv.org/abs/2206.01208
To appear in European Physical Journal

CDR outline:
1. Linac upgrade
2. An accumulator ring
3. A target station and 50 m decay tunnel
4. A near detector placed in the neutrino beam some 250 m downstream of the target statio
5. A far detector 360 km from the target station consisting of 2 large underground tansk filled each with 240’000 m^3 of water
6. Physics performance

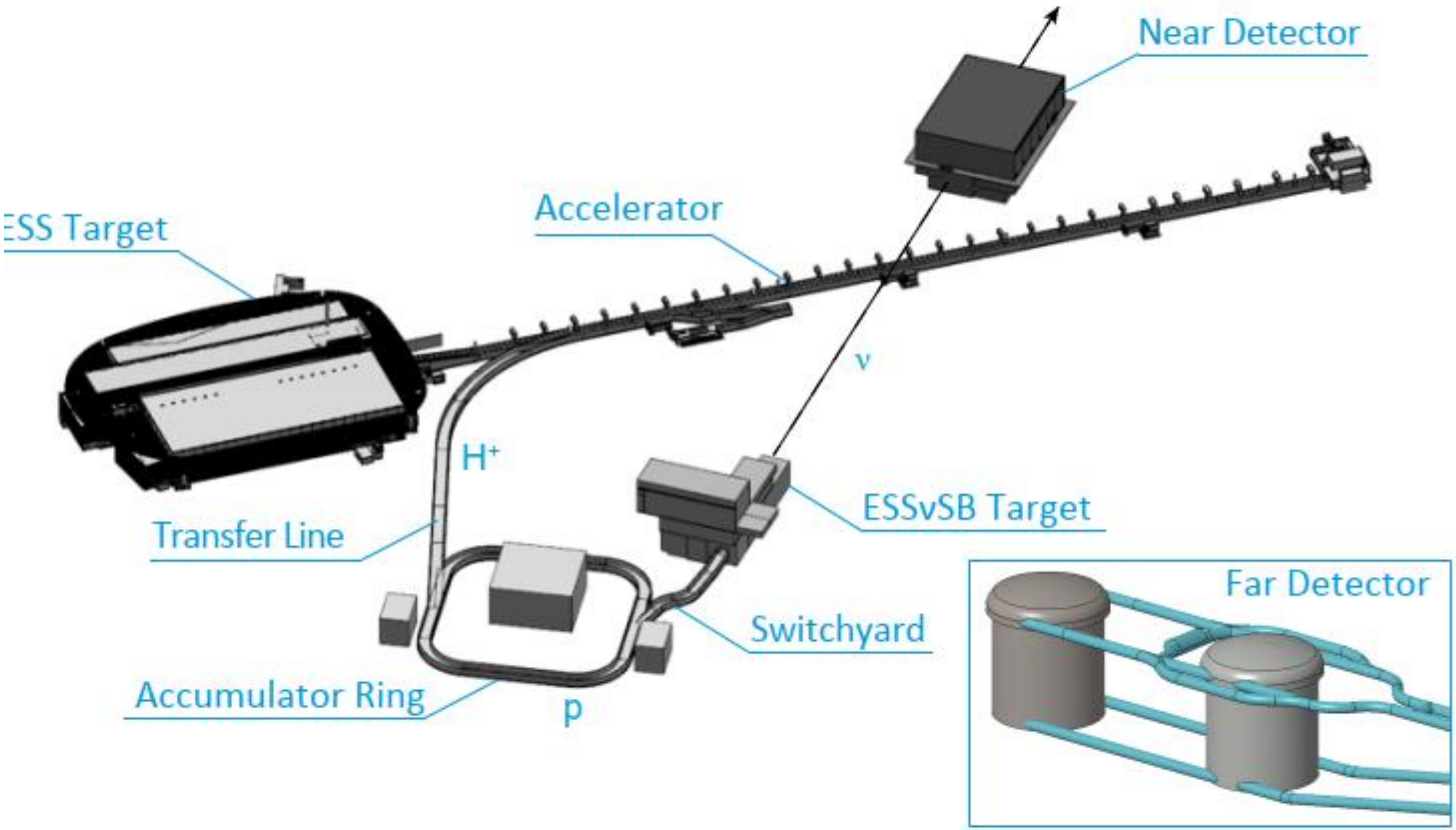
The European Spallation Source neutrino Super Beam

White Paper to be submitted to the Snowmass 2021
USA Particle Physics Community Planning Exercise

arXiv:2203.08803v1 [physics.acc-ph] 15 Mar 2022

https://arxiv.org/abs/2203.08803

ESSnuSB lay-out



The ESS linac

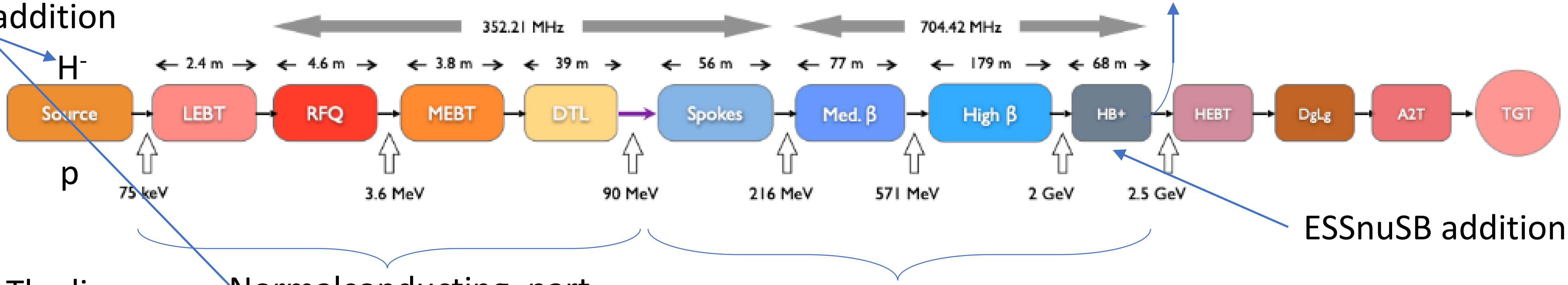
2.86 ms pulses at 14 Hz pulse frequency increase to 28 Hz, implying an increase of the beam power from 5 MW to 10 MW

Transfer Line to Accumulator

ESSnuSB addition

H^-

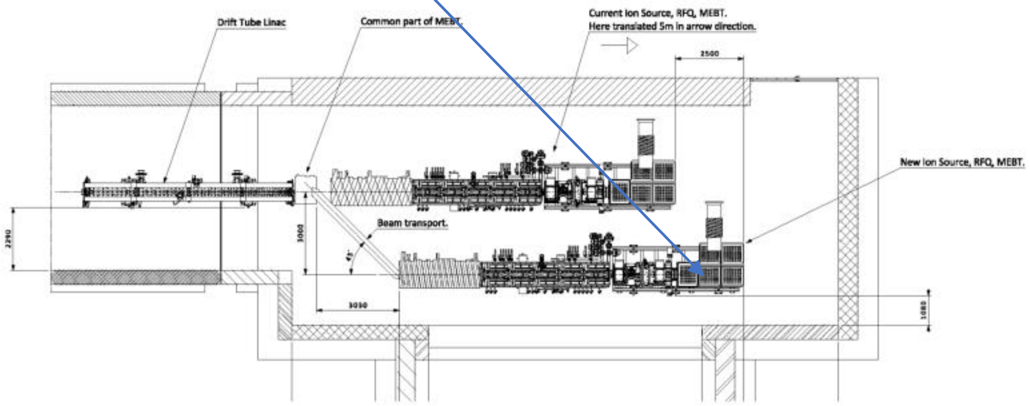
p

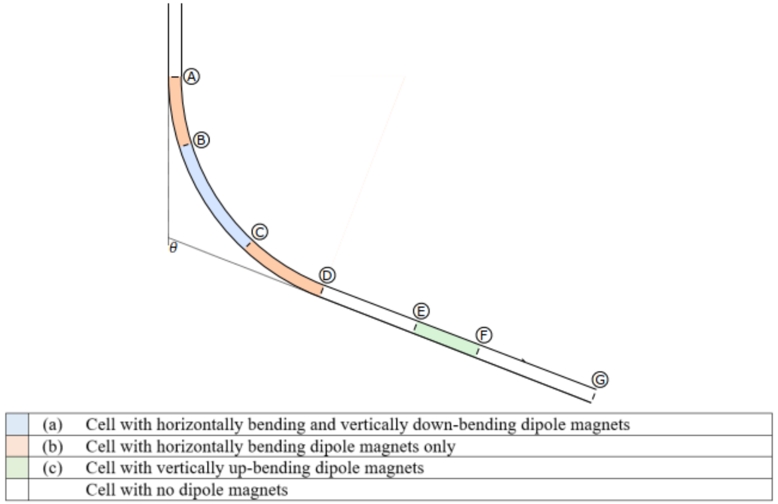


ESSnuSB addition

The linac Normalconducting part

Superconducting part

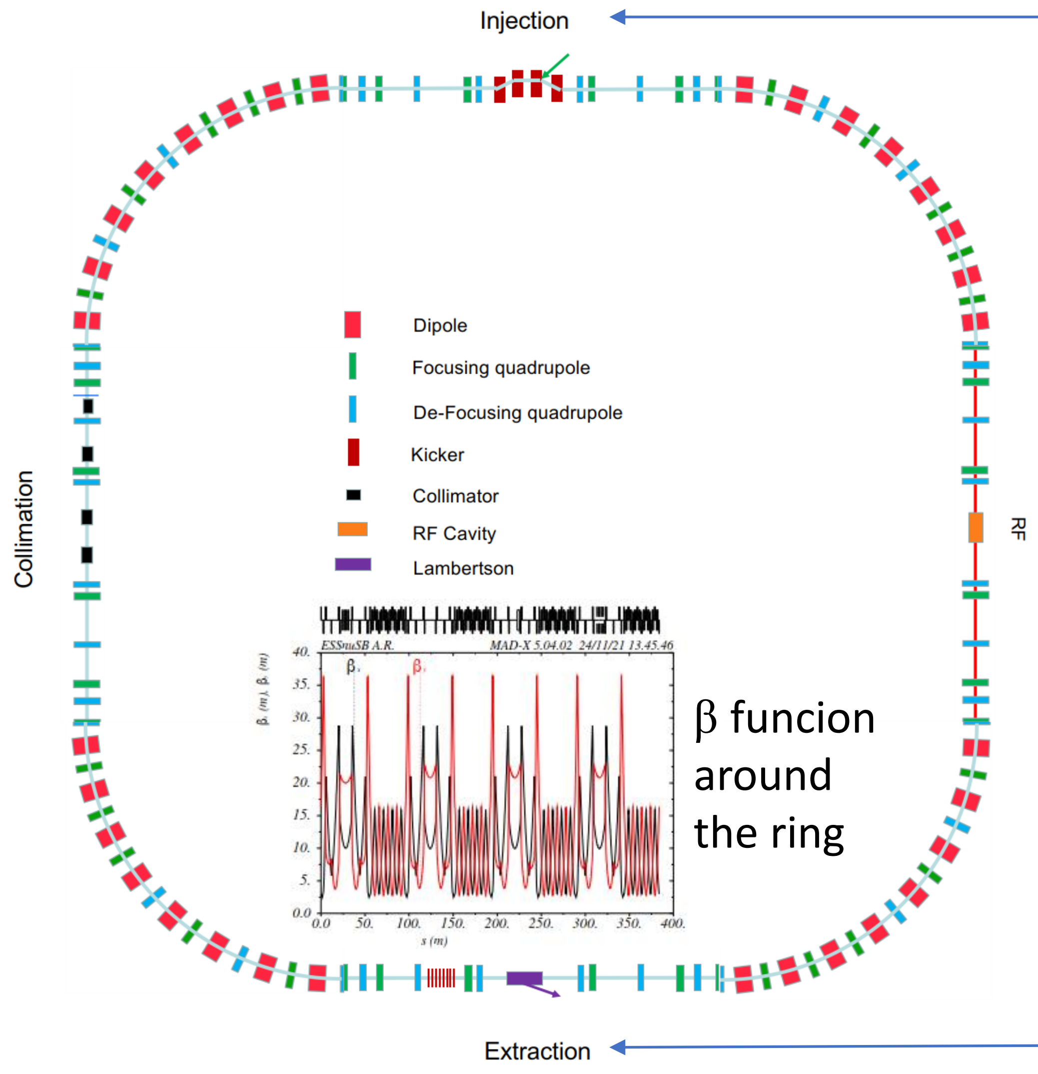




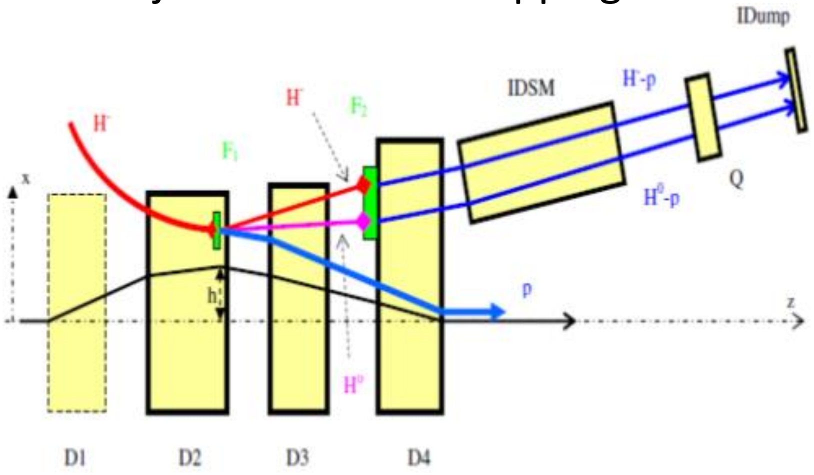
The merging of the H+ and the H- beams in the MEBT

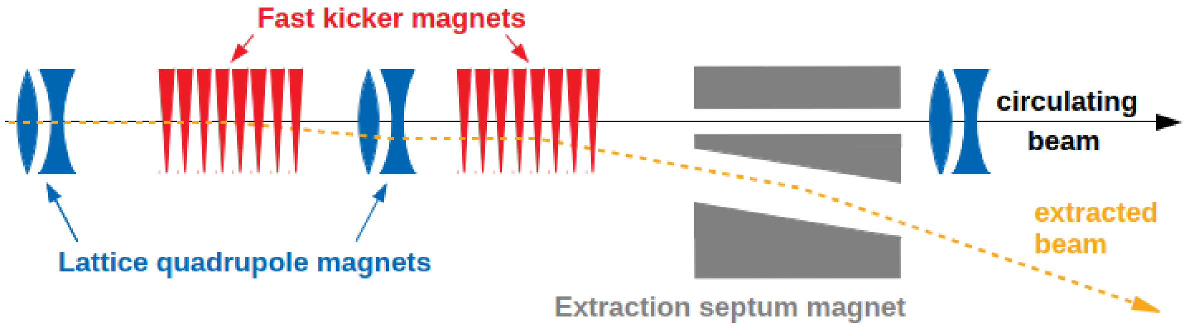
Transfer Line with bending limited by H^- Lorenz stripping

The Accmulator ring



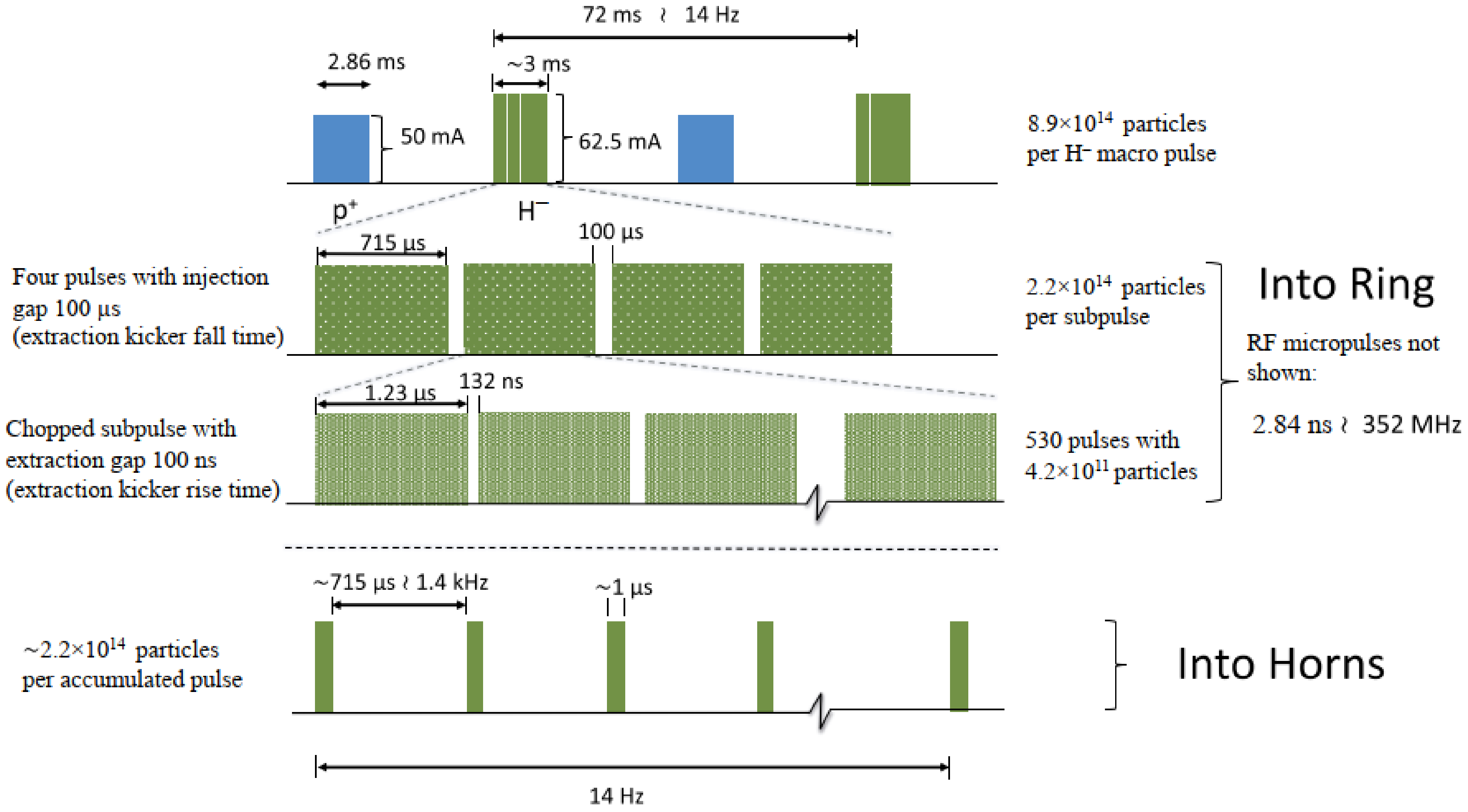
Injection with H- stripping



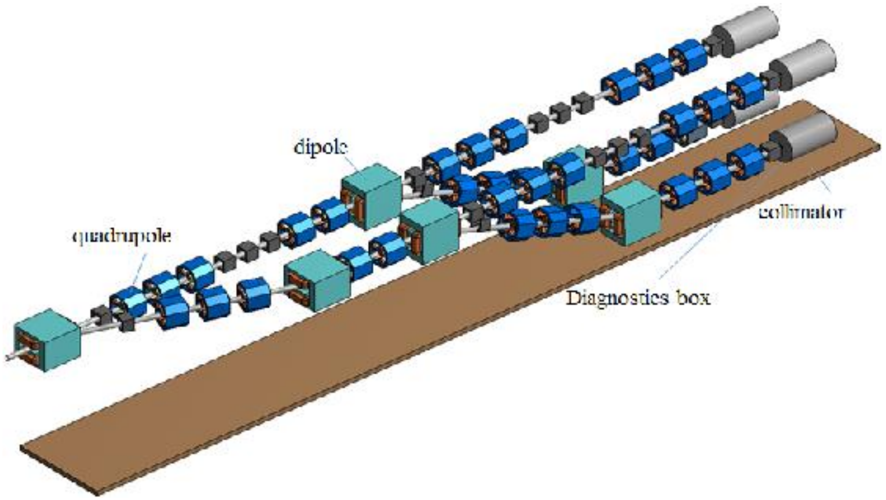


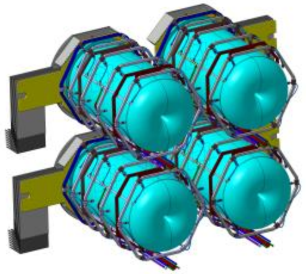
Extraction

Detailed schematic of the ESSvSB pulsing scheme

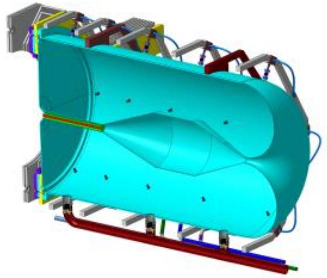


Beam switch-yard and the target station

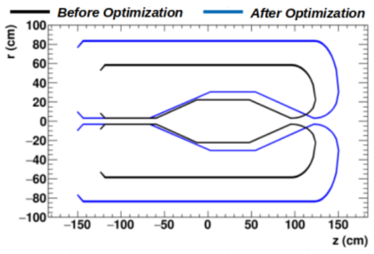




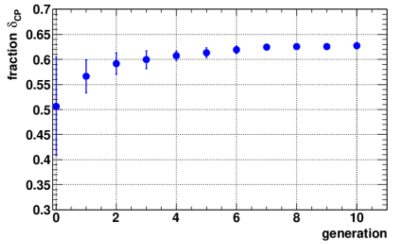
(a) The four-horn system.



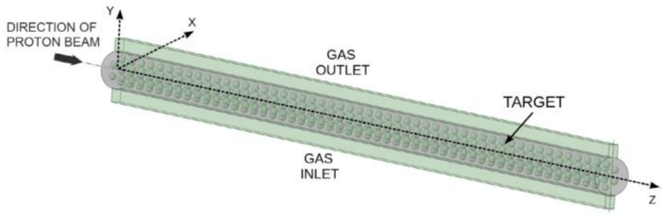
(b) Transverse view of one horn.

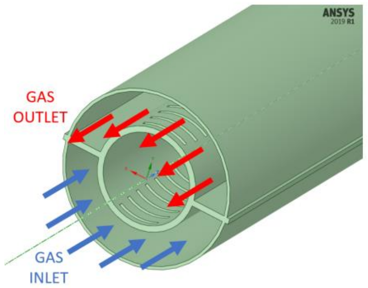


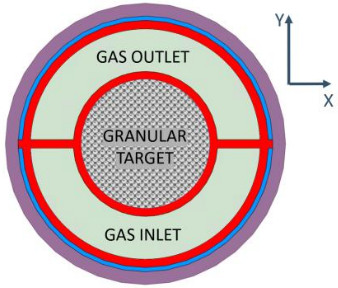
(a) Evolution of the horn profile.



(b) Genetic algorithm convergence throughout the iterative process.







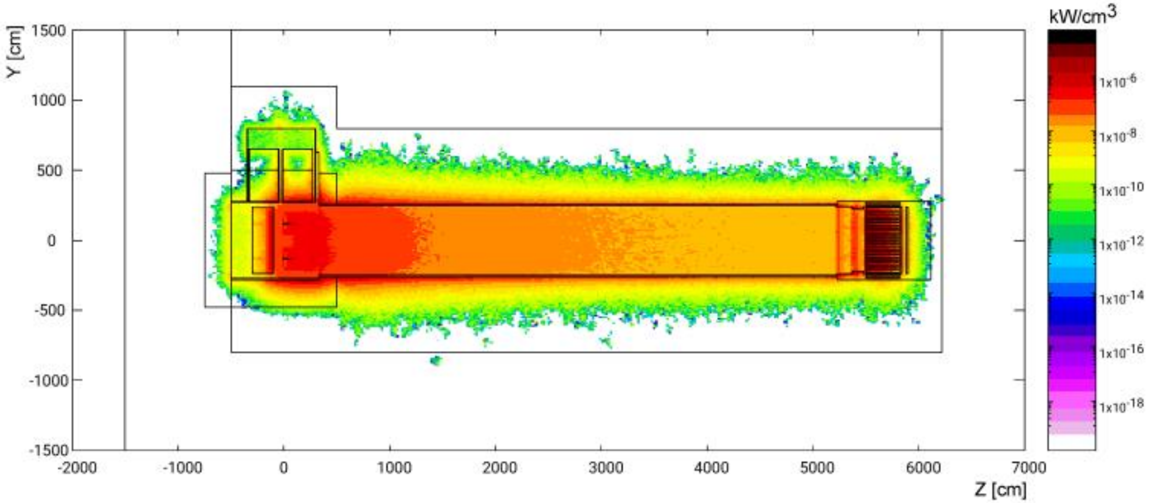
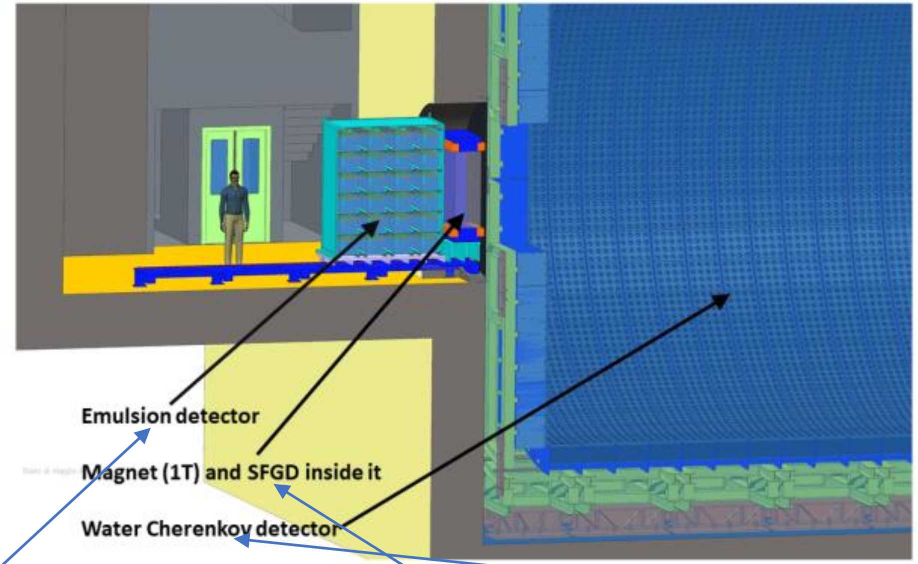
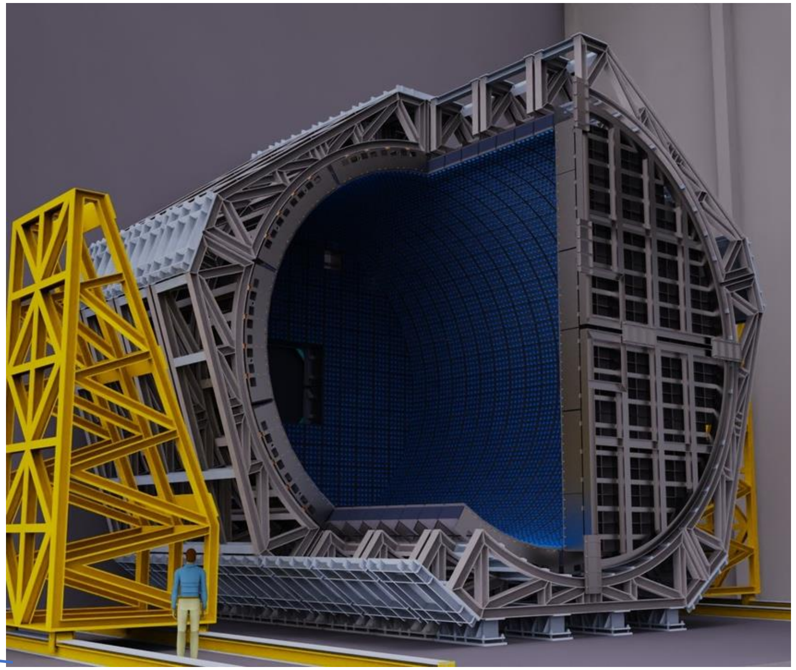


Figure 5.46: Energy deposition distribution in the target station facility.

The Near Detector



Near Detector underground station



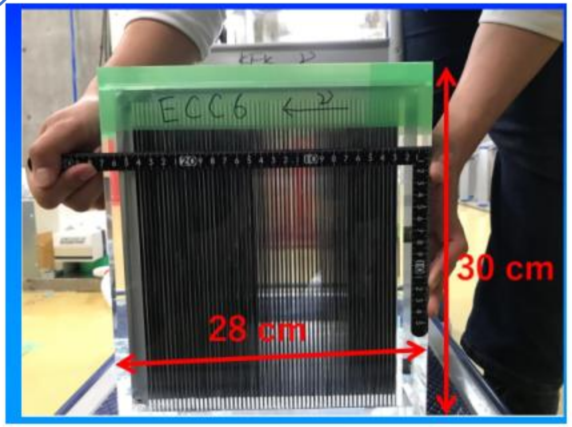
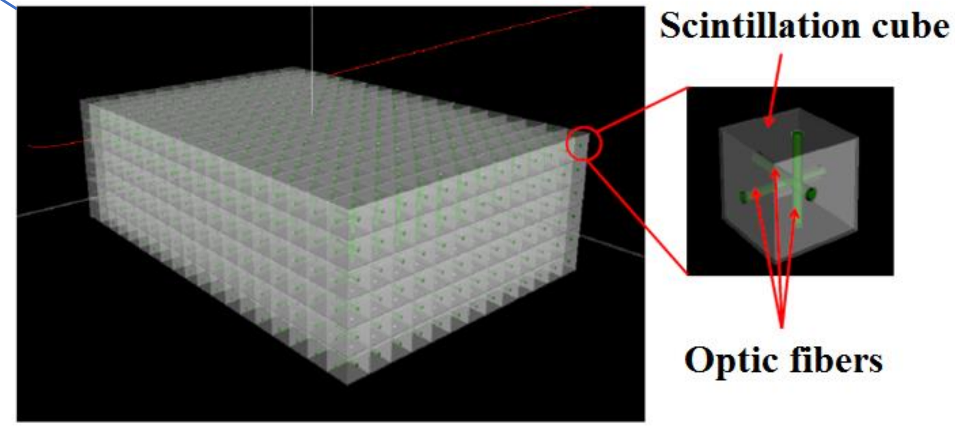
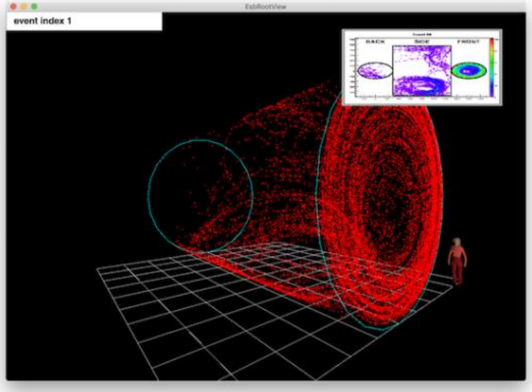


Figure 6.42: A photograph of the NINJA ECC element using water as target.





The super Fine-Grained Detector sFDG

The Far Detector

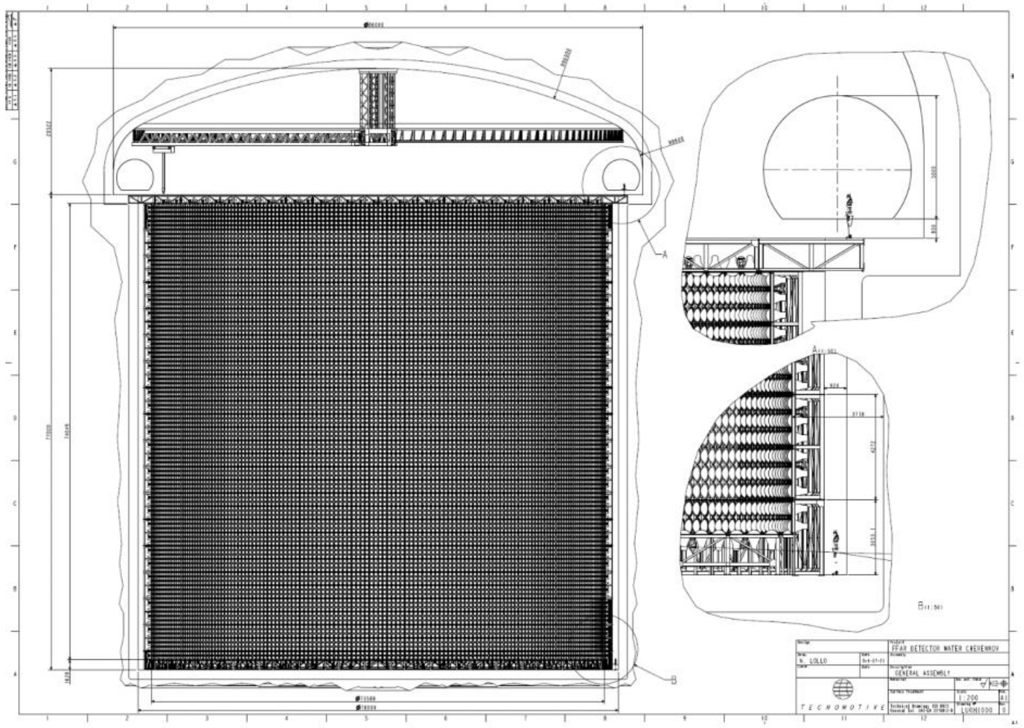


Figure 6.48: Overall view of a single far-detector tank with indicated dimensions.

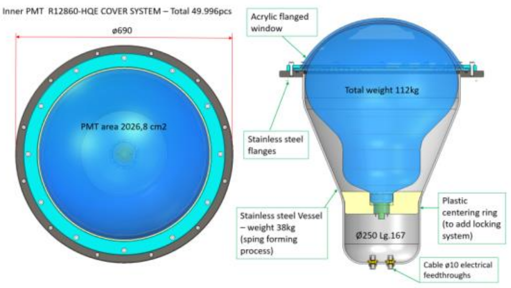
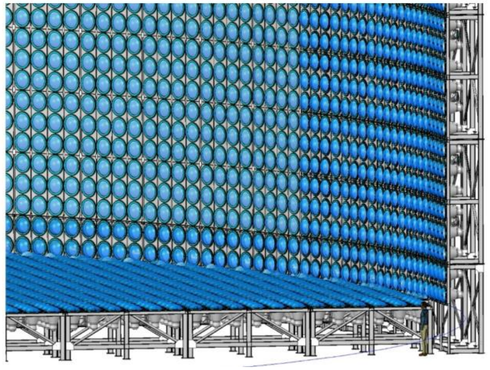
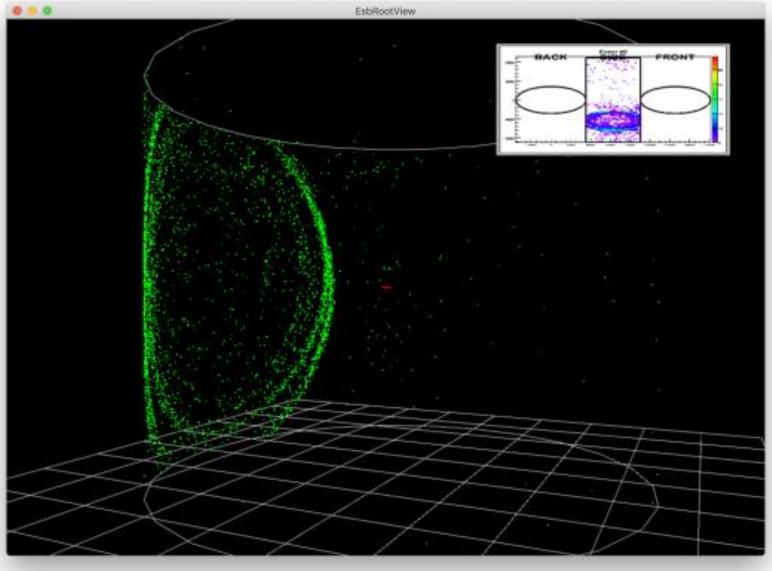


Figure 6.50: A schematic view of an inward-facing 20 inch PMT embedded in a protective cover.





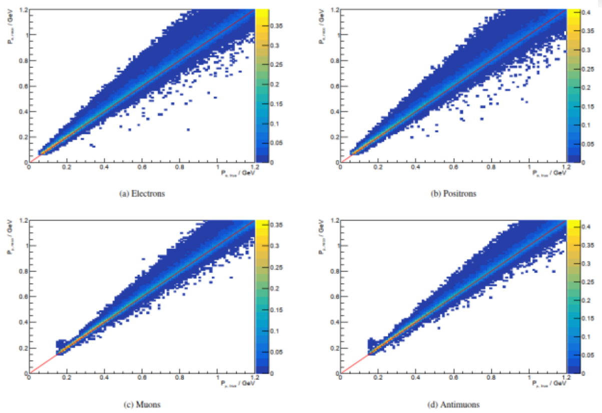
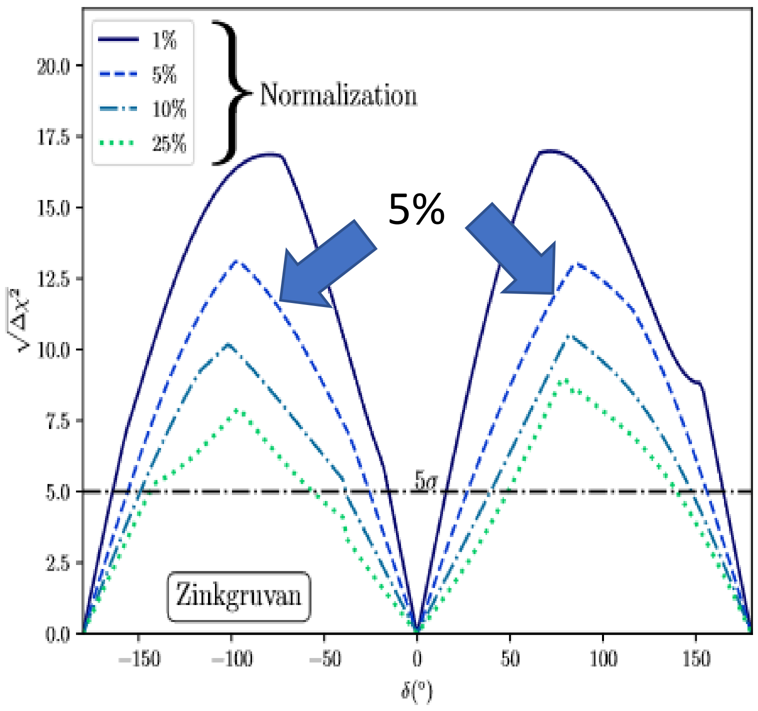


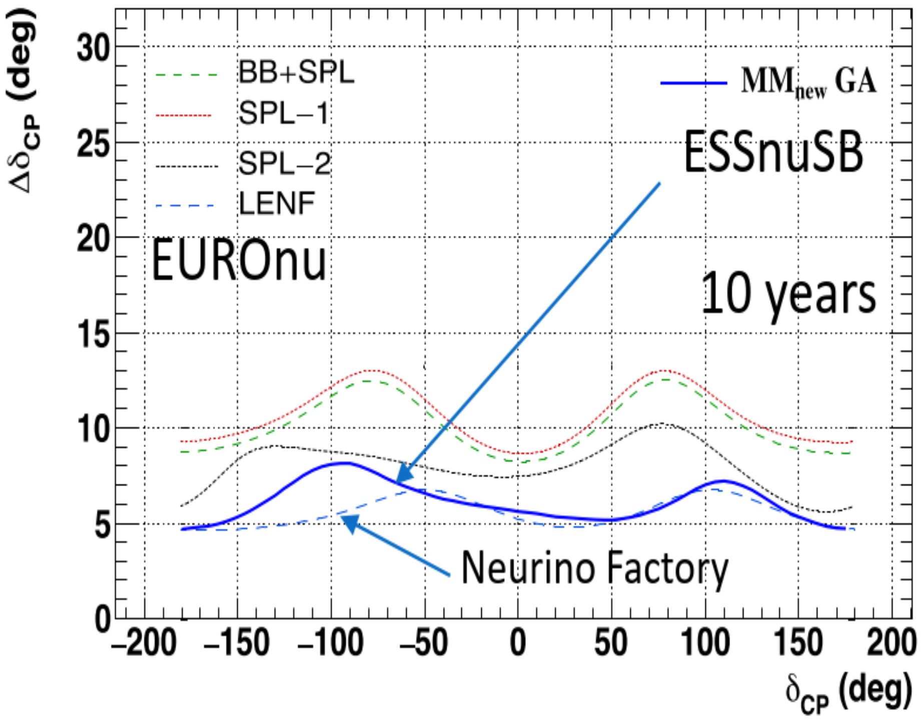
Figure 6.58: Distribution of reconstructed momentum as a function of true momentum for different flavours of charged leptons. These plots were produced using the charged lepton production.

For Cherenkov imagies in the Far Detector see https://drive.google.com/drive/folders/1DidkJRA05GJtm0vFSqpfpCTAooNWAv22

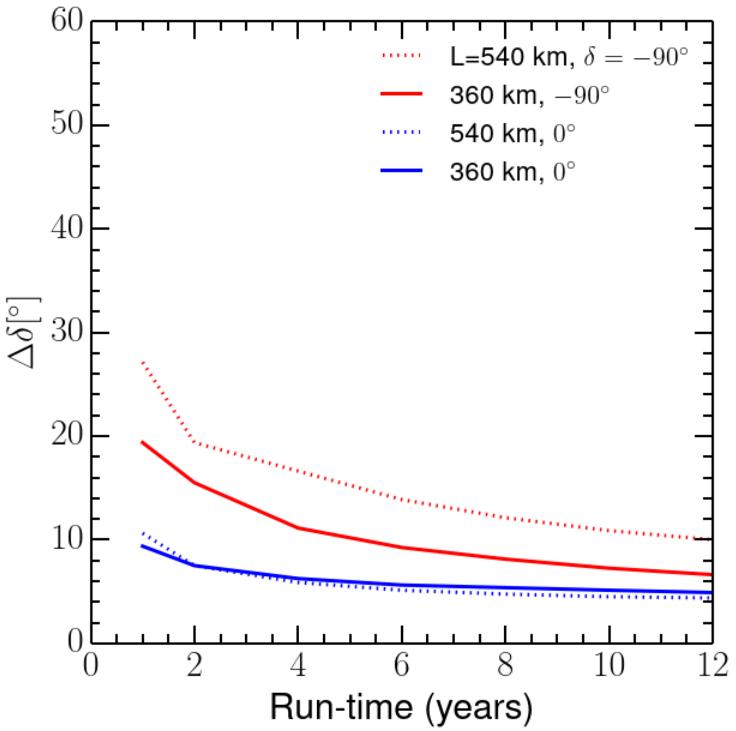
Performance for CPV discovery and δ_{CP} measurement



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

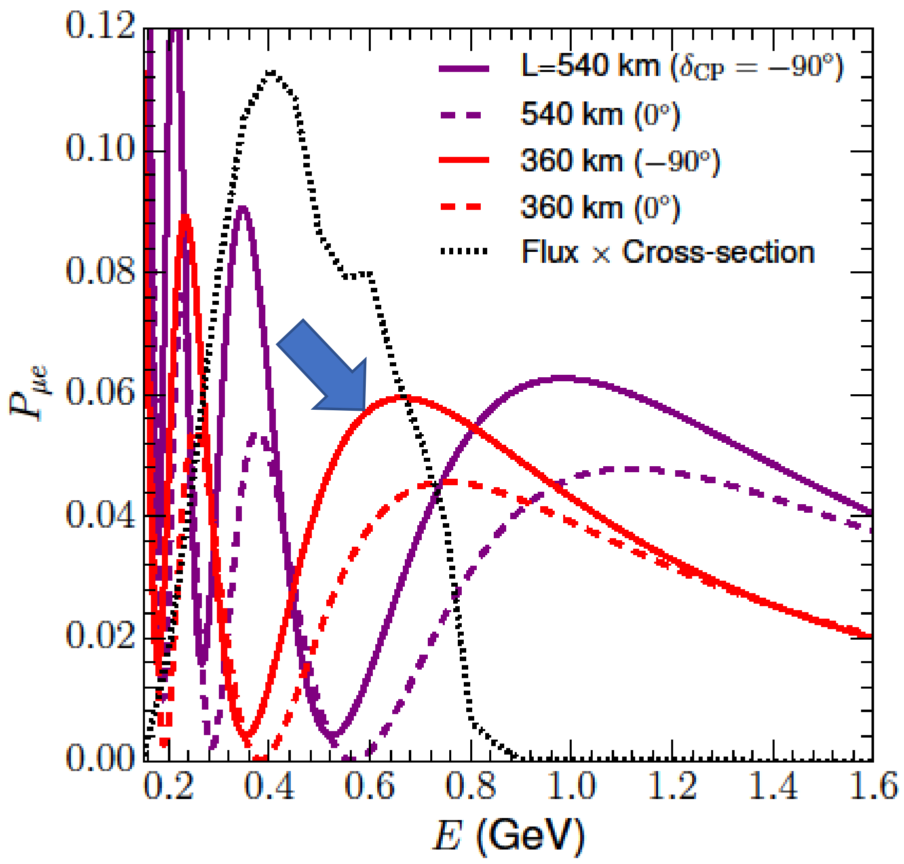


Error in δ_{CP} angle vs δ_{CP} angle after 10 years with 5% normalization error

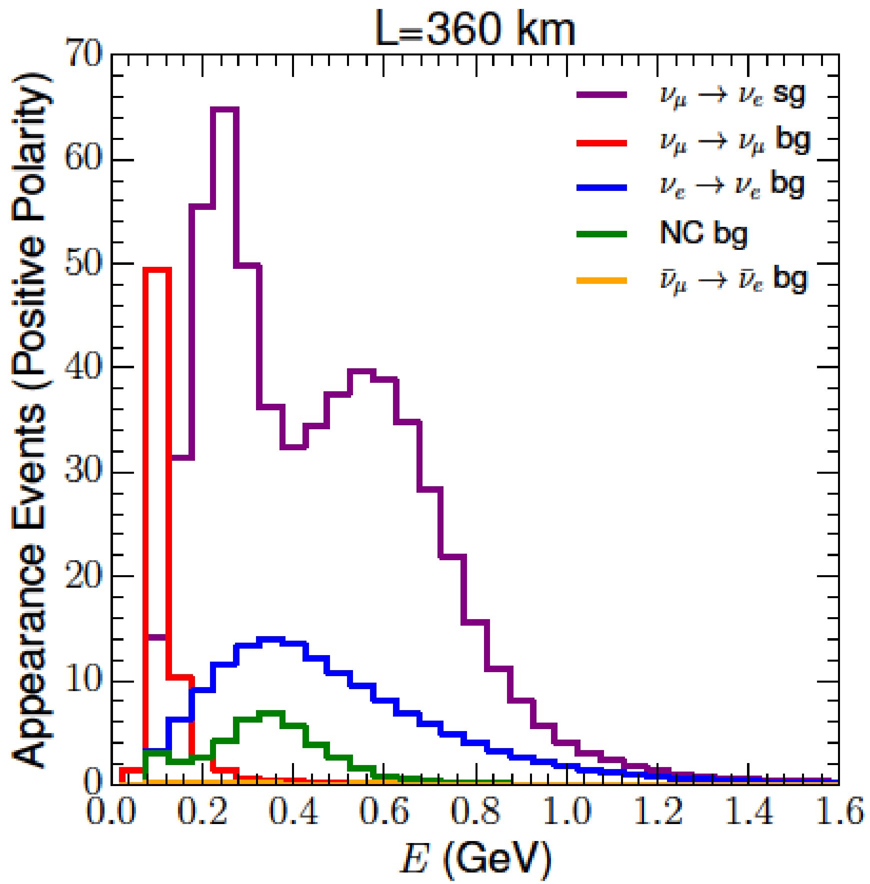


Error in δ_{CP} angle vs run time with 5% normalization error

ESSnuSB at the second neutrino oscillation maximum

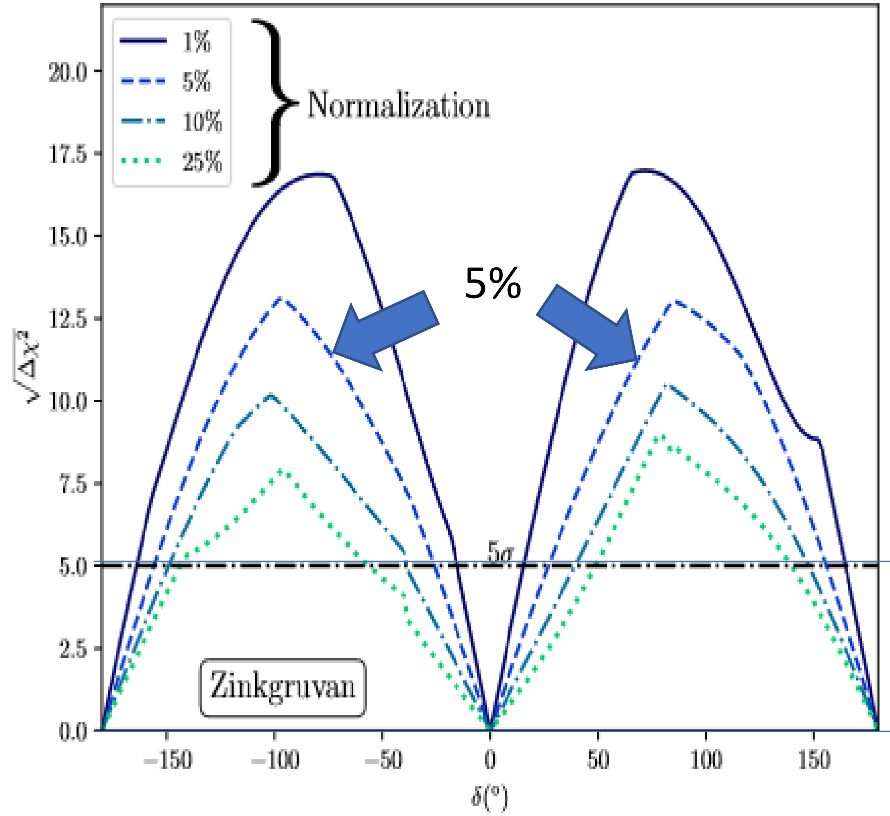


Coverage of the second oscillation maximum

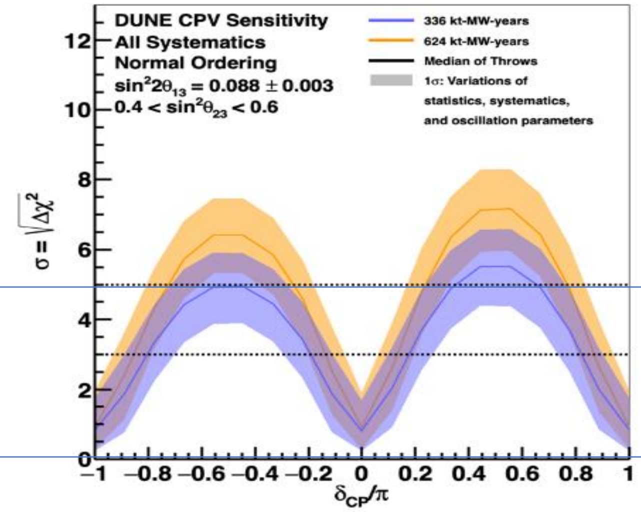


Signal (ν_e) and background energy distributions

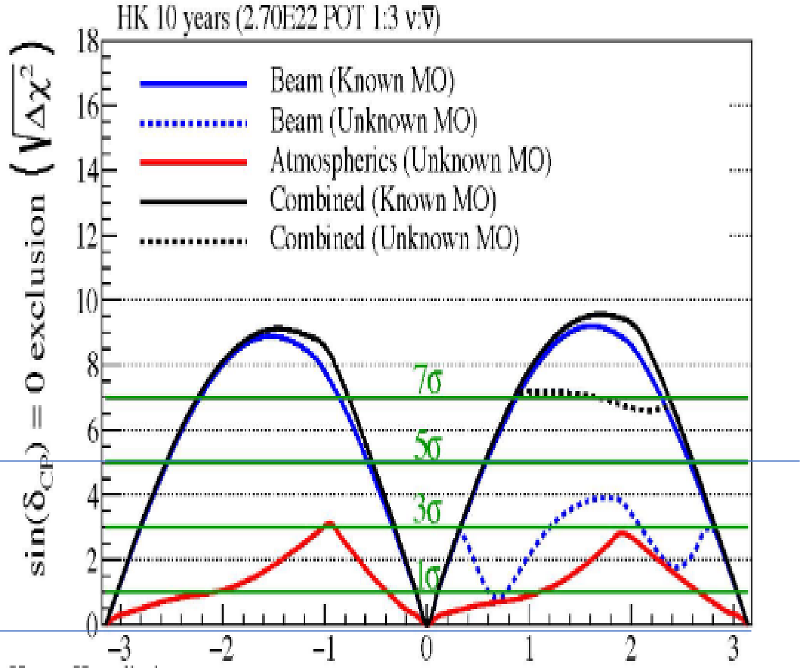
ESSnuSB in the international context – CPV discovery



ESSnuSB March 2022 with 5% normalization error

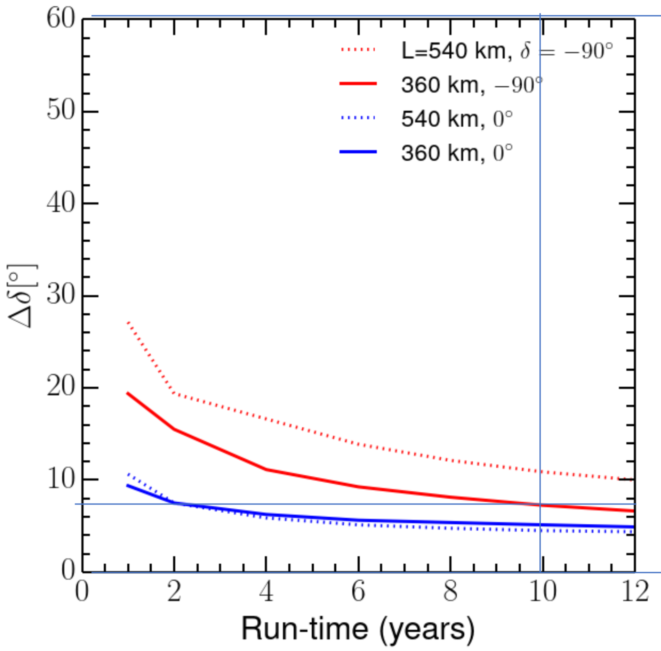


DUNE Snowmass March 2022

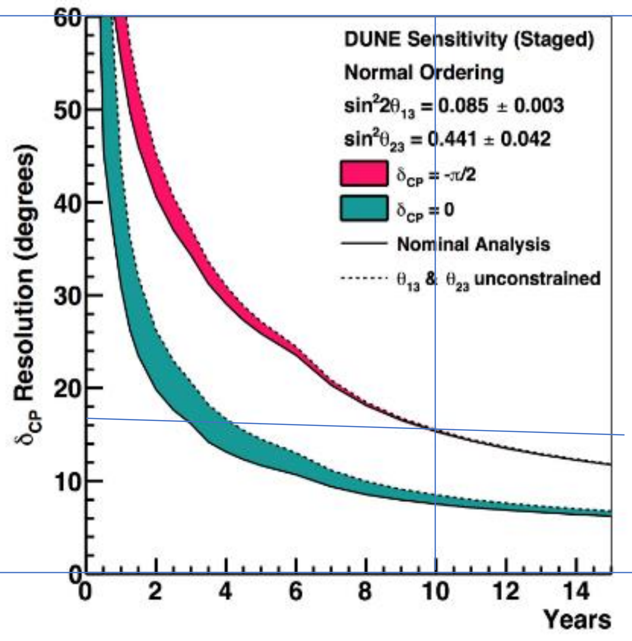


HyperKamokande Snowmass March 2022

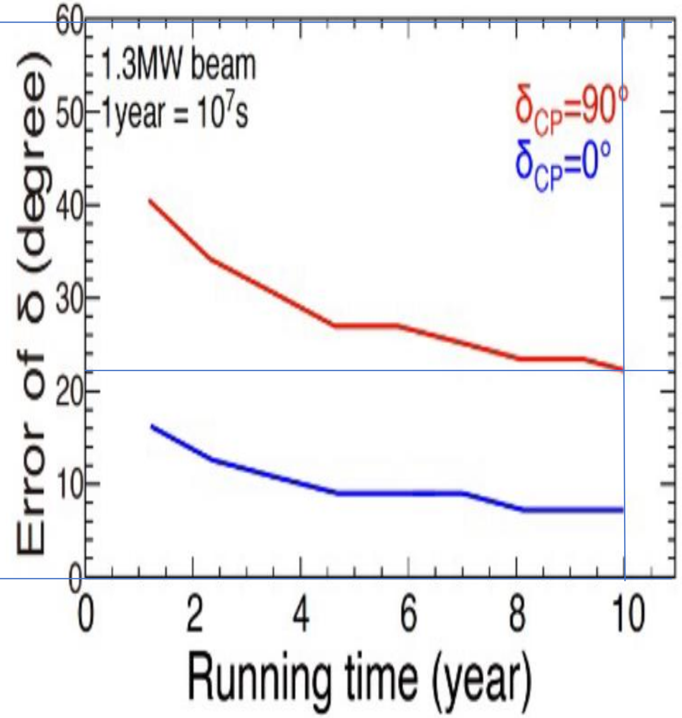
ESSnuSB in the international context – CPV resolution



ESSnuSB March 2022 with 5% normalization error

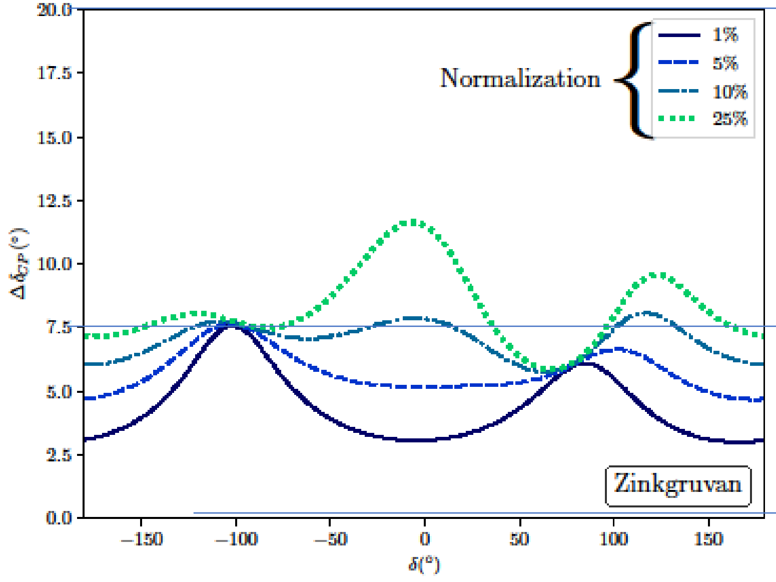


DUNE Snomass March 2022

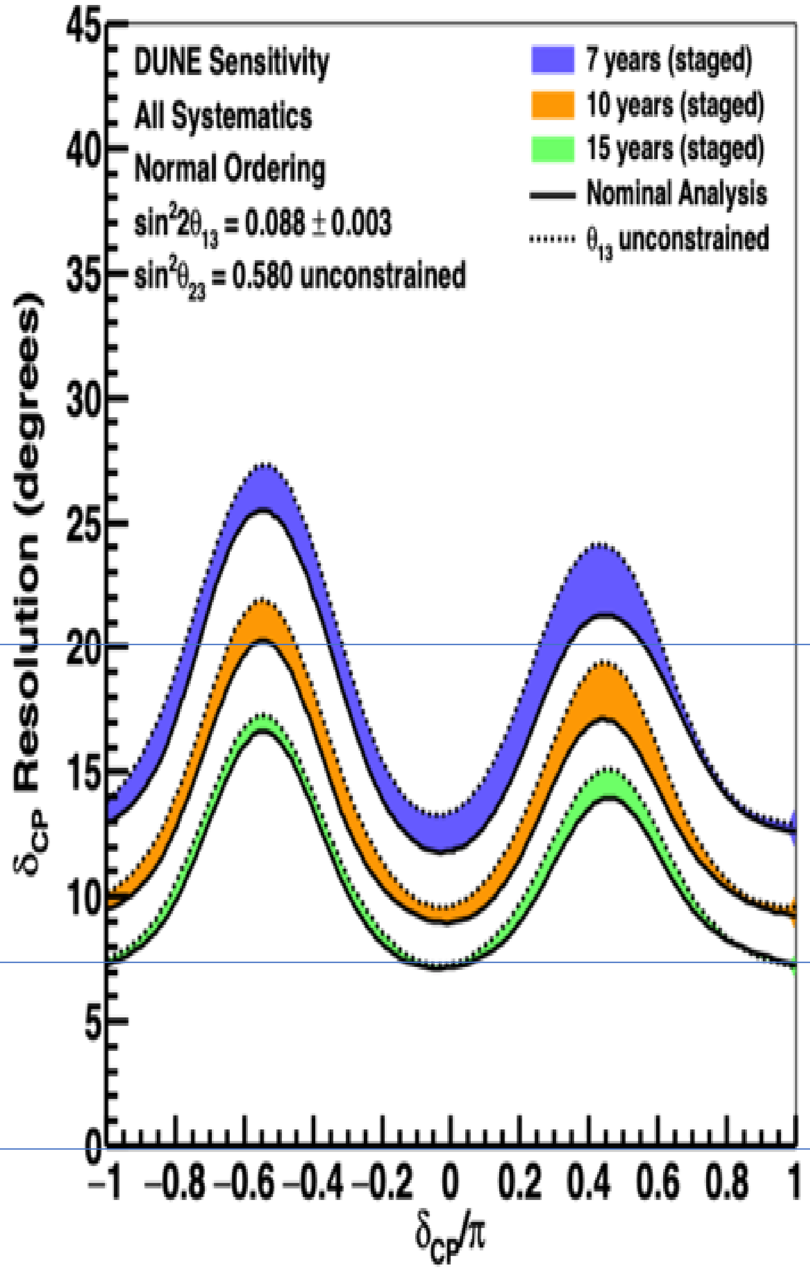


HyperKamokandeSnowmass March 2022

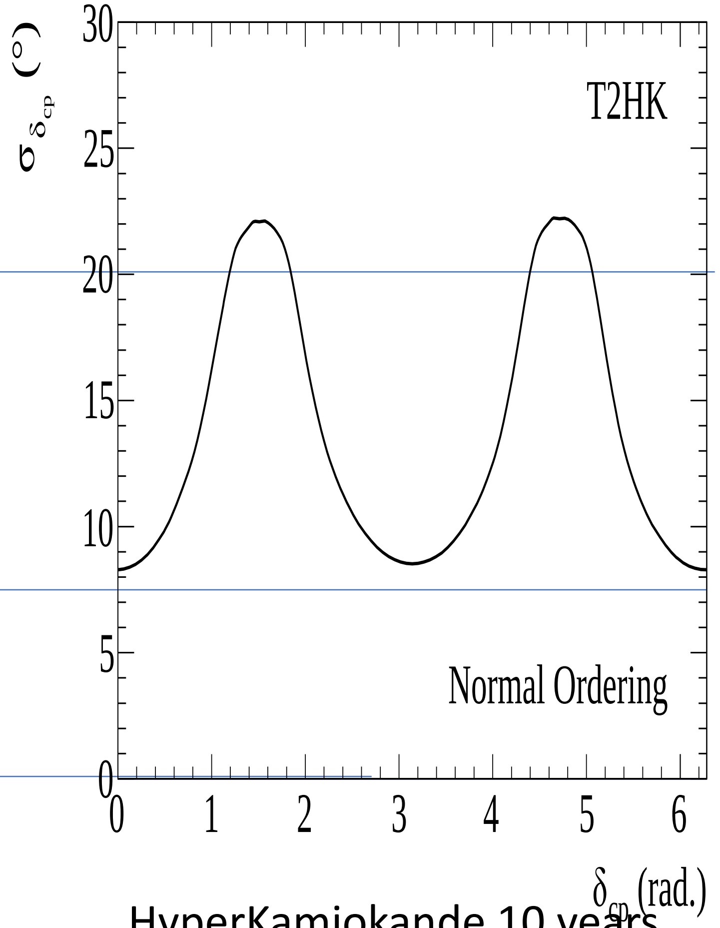
ESSnuSB in the international context – precision in δ_{CP}



ESSnuSB 10 years



DUNE 10 years yellow curve



HyperKamiokande 10 years

ESSnuSB support letters from 4 ESS Director Generals:

Jim Jeck 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
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P.O. Box 176
SE-221 00 Lund
SWEDEN
www.esss.se

John Womersly 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
SE-221 00 Lund
SWEDEN
www.ess.se

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
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P.O. Box 176
SE-221 00 Lund
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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."

European Particle Physics Strategy

Conclusions:

"**The design studies for next-generation long-baseline neutrino facilities should continue.** "

"The first priority is the completion of the programme of measurements of the oscillation parameters, most notably the CP-violating phase of the mixing matrix and the neutrino mass ordering."

"Future European facilities such as FAIR, NICA and ESS envisage research programmes that are of interest to particle physics."

"The European particle physics community should work with the European Commission to shape and establish the funding instruments that are required for the realisation of common R&D projects, e.g. in the Horizon Europe programme."

"A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry."

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%**

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

2012: Inception of the project

Nucl. Phys. B 885 (2014) 127

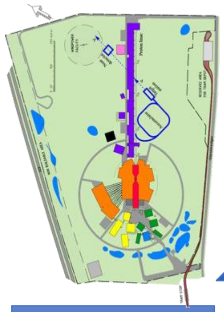
2016-2019: Beginning of COST Action EuroNuNet

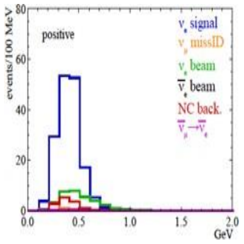
2018: Beginning of ESSνSB Design Study (EU-H2020)

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

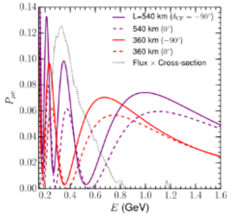
2023-2026: Continuation of Design Study, final costing and an TDR to ESFRI

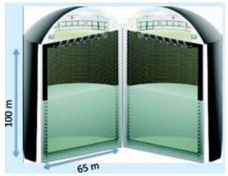
2027-2028: Preconstruction Phase, International Agreements





2029-2035: Construction of the facility an detectors, including commissionin





2036-: Start of data taking

Thank you