Journées Accélérateurs 2021 de la SFP
Roscoff
12-15 octobre 2021

The ESSνSB neutrino superbeam

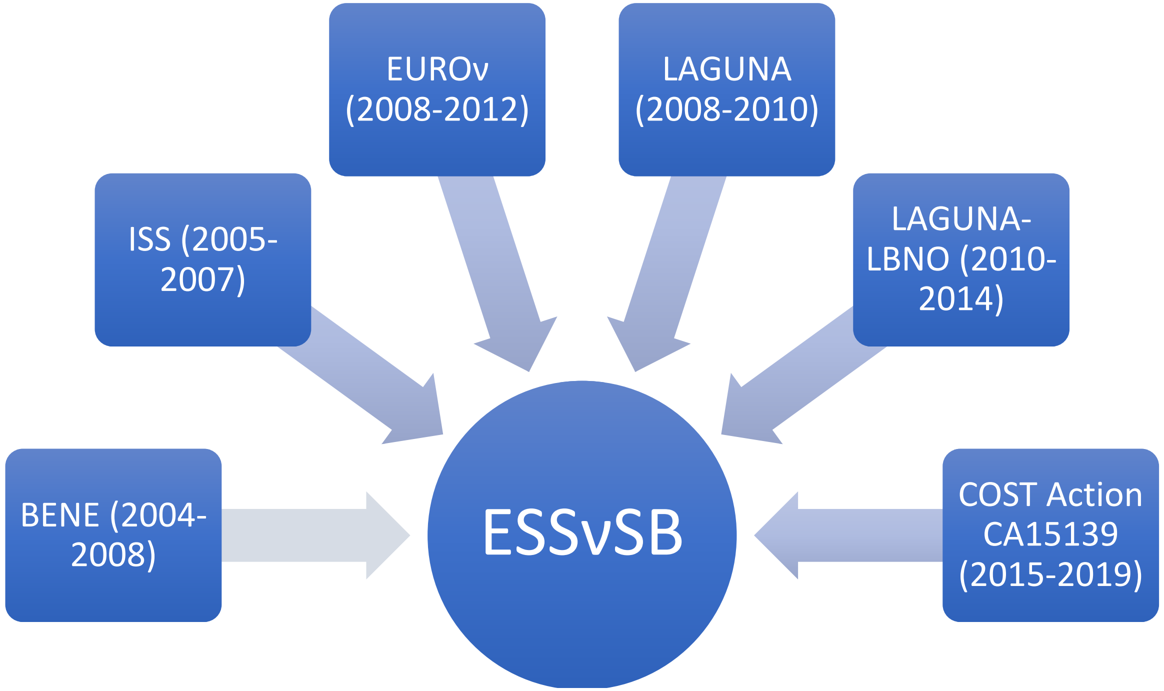
E. Baussan on behalf of ESSνSB collaboration
IPHC-IN2P3/CNRS Strasbourg

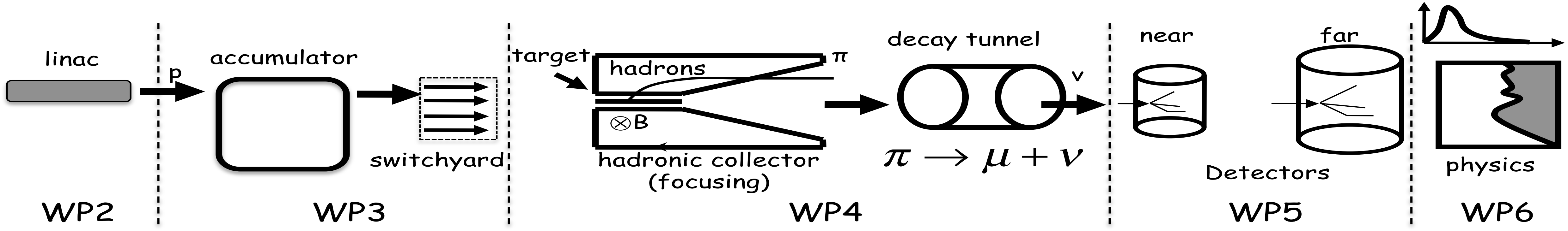
ESS NEUTRINO SUPER BEAM
Funded by the Horizon 2020 Framework Programme of the European Union

The ESSνSB Superbeam : a neutrino beam in Europe

Funded by the Horizon 2020 Framework Programme of the European Union

- **Title of Proposal**: Discovery and measurement **of leptonic CP violation** using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator
- **Duration: 4 years**
- **Total cost: 4.7 M€**
- **Requested budget: 3 M€**
- 15 participating institutes from
  11 European countries including CERN and ESS
- 6 Work Packages





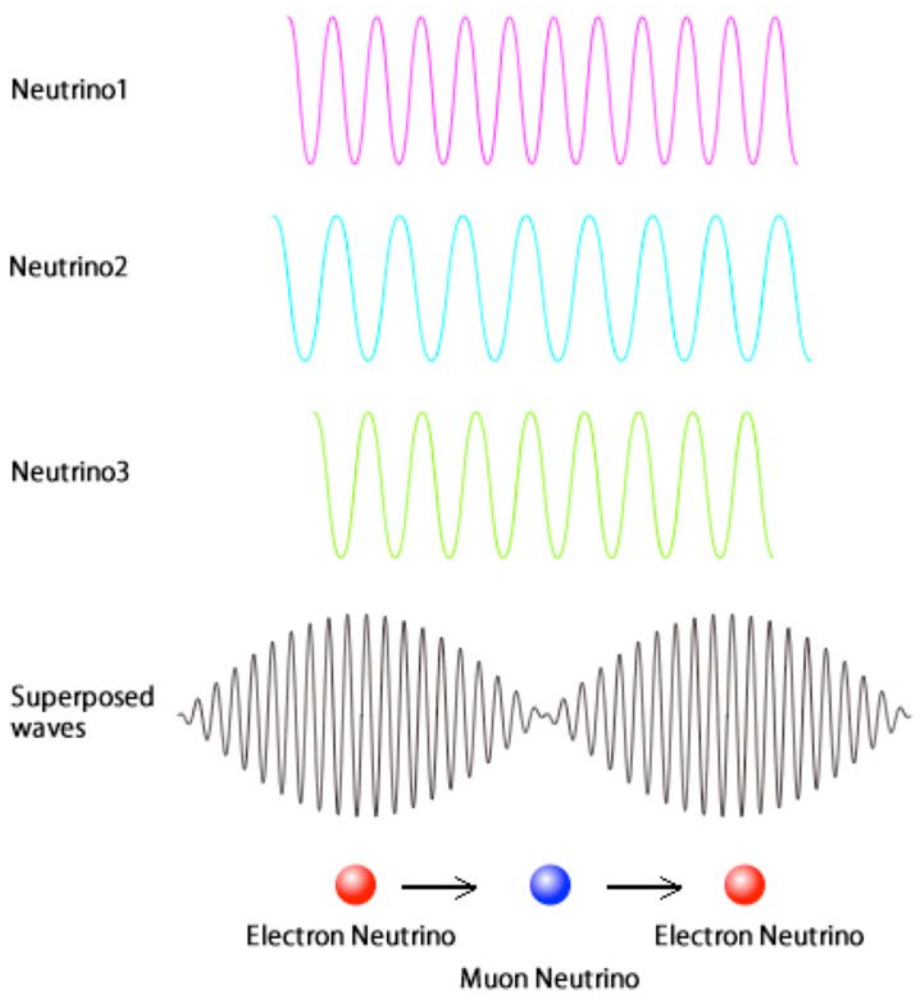
ESSνSB has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 777419

Neutrino mixing :

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix} 1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Flavor Eigenstates | Solar, Reactors | Atmospheric, Accelerator | δ_{CP} Violation Term | Mass Eigenstates

With $c_{ij}=\cos(\theta_{ij})$, $s_{ij}=\sin(\theta_{ij})$ and δ_{CP} CP violation phase



Oscillation probability:

$$P(\nu_\ell \to \nu_{\ell'}) = \left|\sum_i U_{\ell i}U^*_{\ell' i} e^{-i(m_i^2/2E)L}\right|^2$$

$$= \sum_i |U_{\ell i}U^*_{\ell' i}|^2 + \Re \sum_i \sum_{j\neq i} U_{\ell i}U^*_{\ell' i}U^*_{\ell j}U_{\ell' j} e^{i\frac{|m_i^2-m_j^2|L}{2E}}$$

L distance from source; E energy; $\Delta m^2_{ij} = m^2_i - m^2_j$

The ESSνSB Superbeam : Physics and Baseline

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Oscillation probability $P(\nu_\mu \to \nu_e)$:

$$P_{\nu_\mu\to\nu_e(\bar{\nu}_\mu\to\bar{\nu}_e)} = s_{23}^2 \sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right) \quad \text{atmospheric}$$

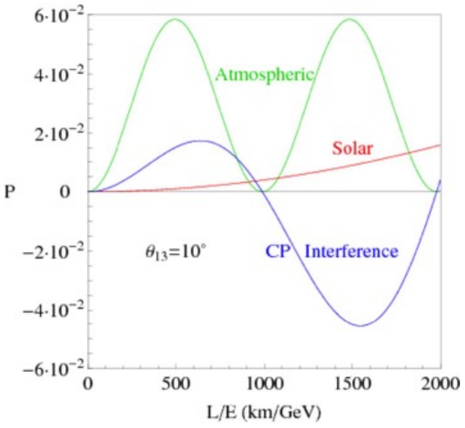
$$+c_{23}^2 \sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right) \quad \text{solar}$$

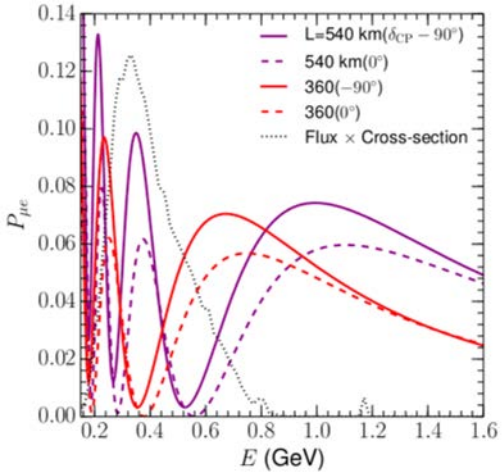
$$+\tilde{J}\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{\tilde{B}_\mp}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde{B}_\mp L}{2}\right)\cos\left(\pm\delta_{CP}-\frac{\Delta_{13}L}{2}\right) \quad \text{interference}$$

Non-CP terms

$$\tilde{J} \equiv c_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13},\ \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu},\ \tilde{B}_\mp \equiv |A \mp \Delta_{13}|,\ A = \sqrt{2}G_F N_e$$

CP violating





$$\mathcal{A} = \frac{P_{\nu_\mu\to\nu_e} - P_{\bar{\nu}_\mu\to\bar{\nu}_e}}{P_{\nu_\mu\to\nu_e} + P_{\bar{\nu}_\mu\to\bar{\nu}_e}}$$

≠0 ⇒ CP Violation be careful, matter effects also create asymmetry

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

→ More sensitivity on 2nd Osc. Maximum

The ESSνSB Superbeam : Physics and Baseline

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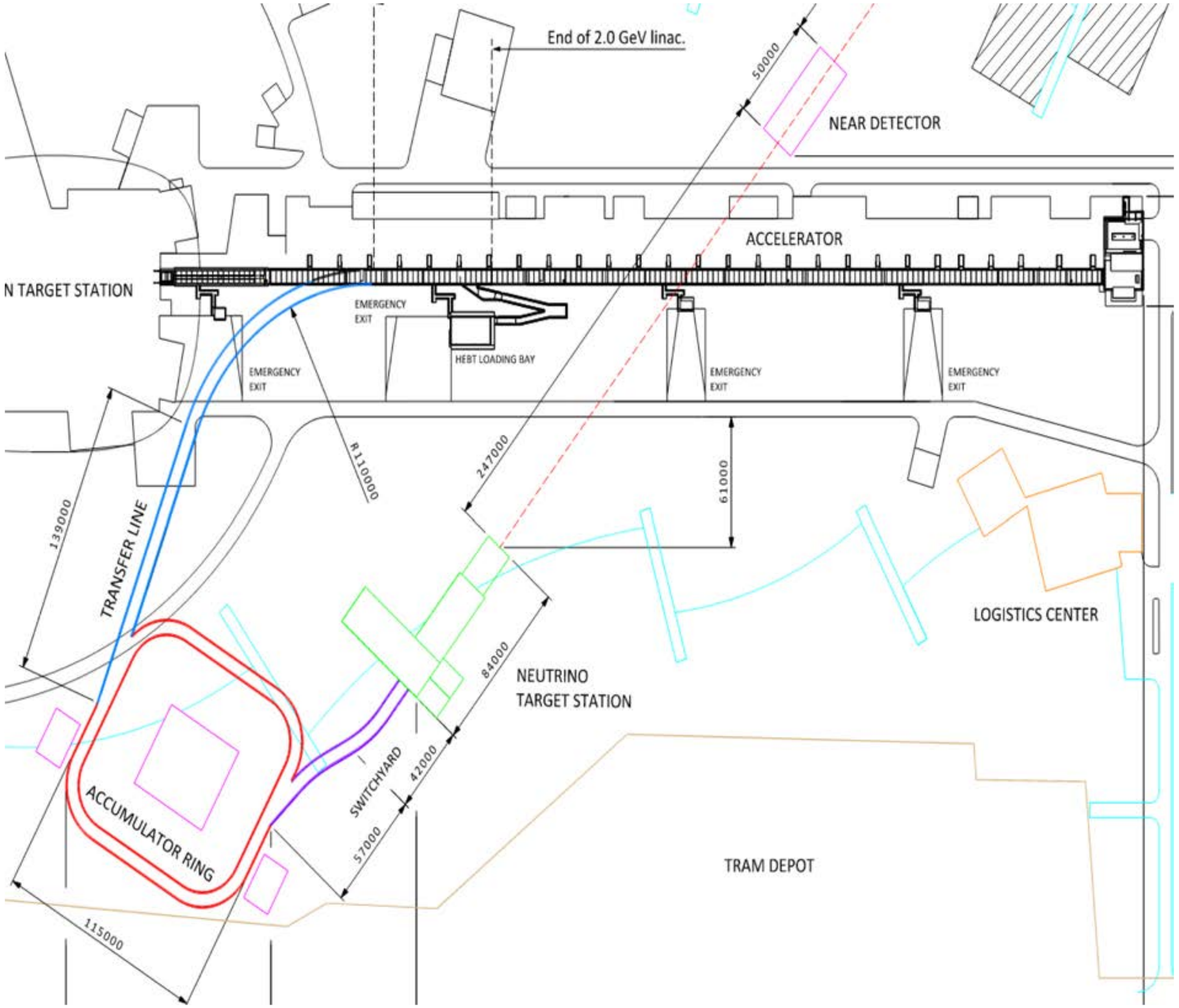

The ESSνSB Superbeam : Linac Modification

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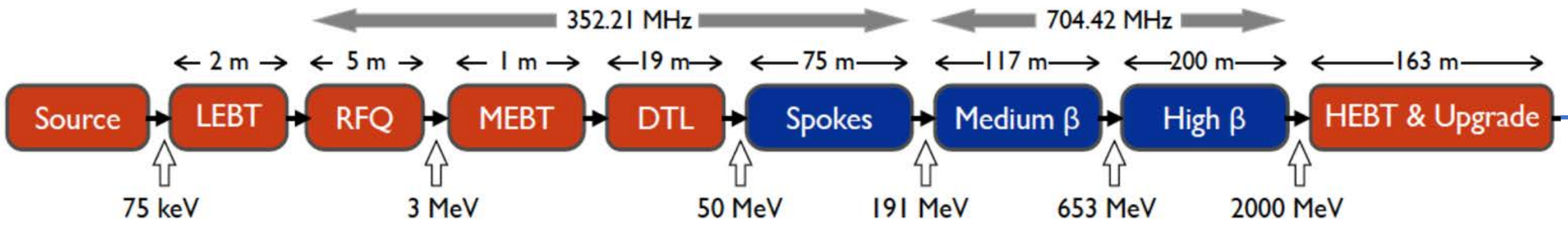
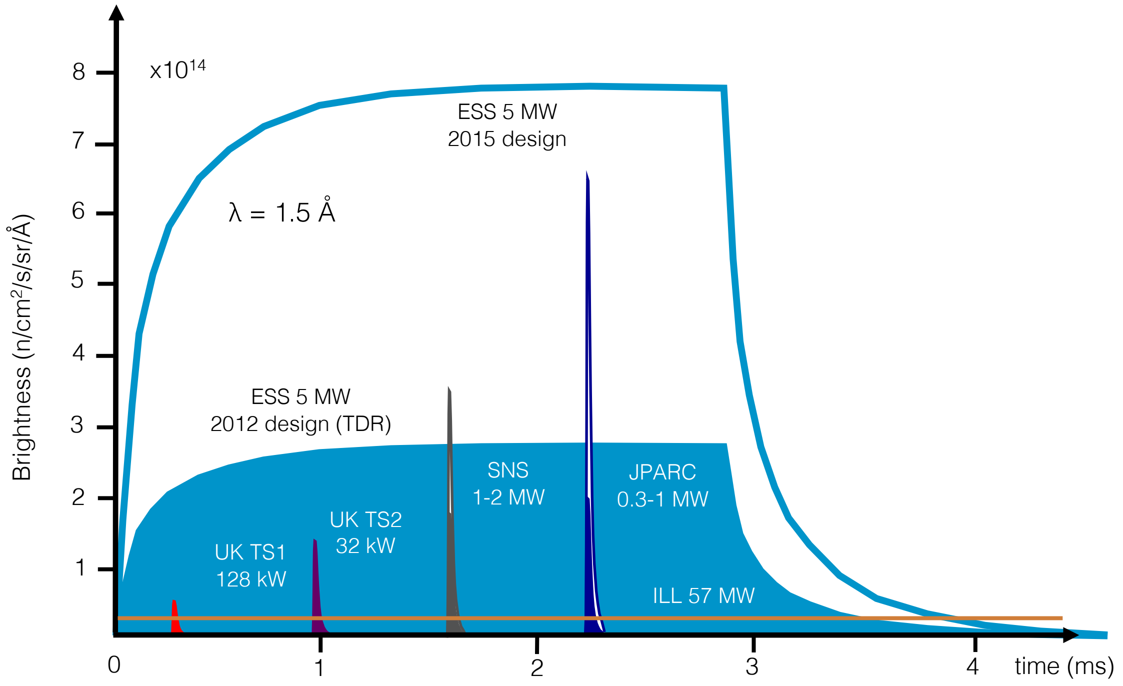


5 MW proton beam for neutron users (2.86 ms pulse width)

- 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).
- Duty cycle 4%.
- 2.0 GeV kinetic energy protons



The ESSνSB Superbeam : Linac Modification

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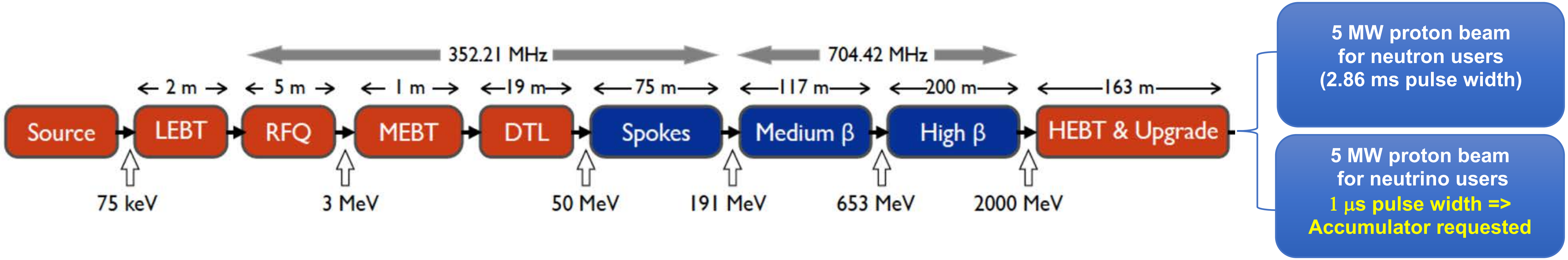
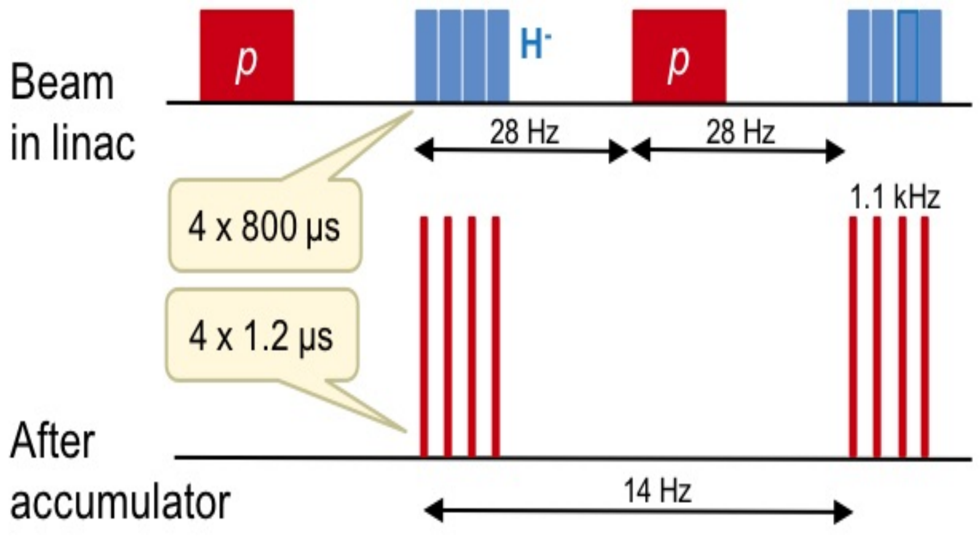


- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power => 10 MW
- 125 MW peak power.
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons).
- Duty cycle 4% => Duty cycle 8%
- 2.0 GeV kinetic energy protons => 2.5 GeV
- Accumulator ring to shorten the pulses to μs order for the horn
- Extra H^- source



Proton beam pulses

The ESSνSB Superbeam : Accumulator & switchyard

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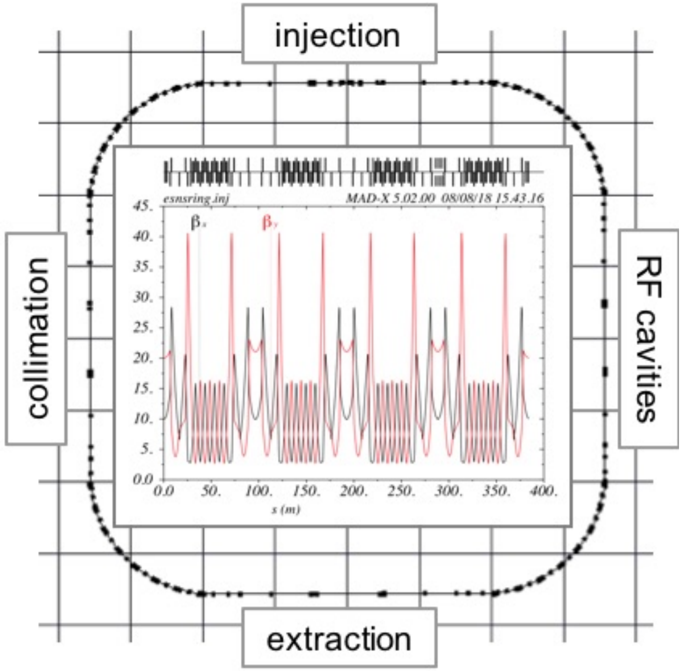
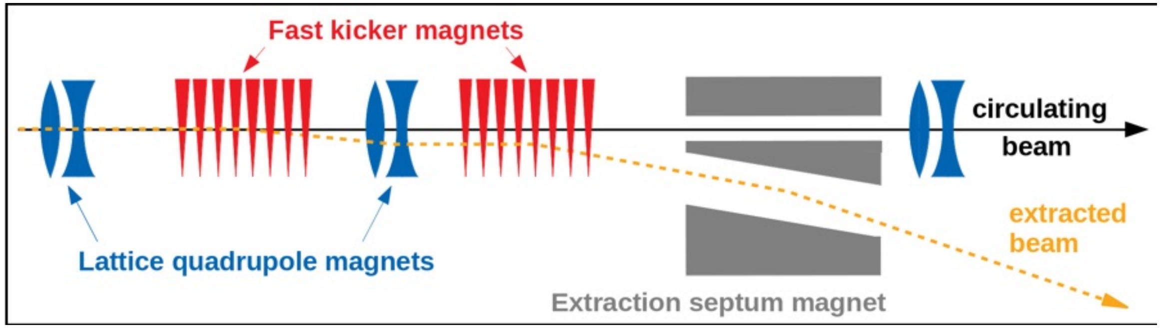
Accumulator

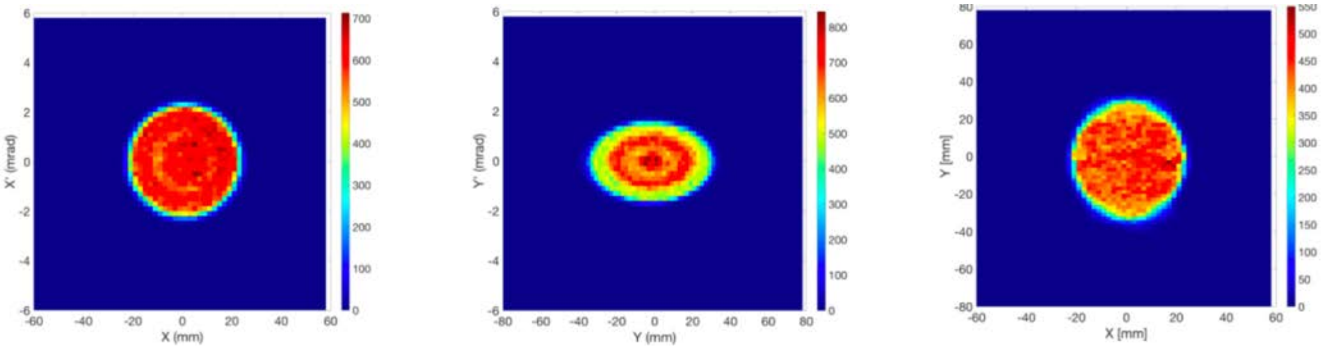
- 384 m circumference (4 arcs, 4 straight sections).
- H- stripping using foil.
- Laser-assisted stripping also considered.
- Correlated and anticorrelated painting of the beam.
- Geom emittance at the switchyard: 70 π mm mrad.

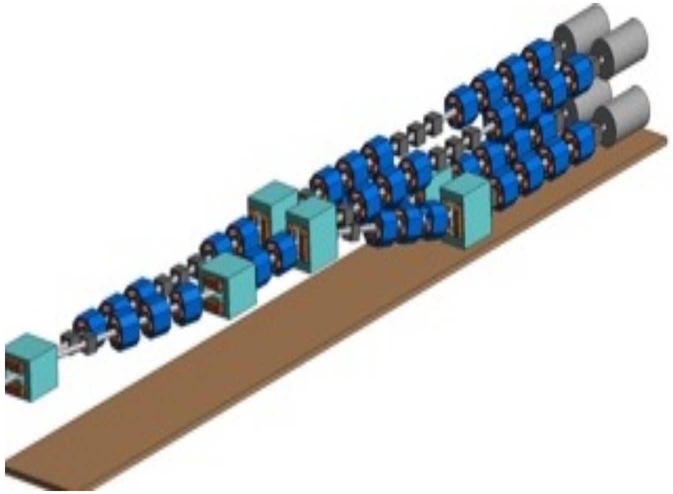


Ring-to-switchyard transfer line and beam switchyard bring the proton pulses from the ring extraction to the beam switchyard and distribute the resulting four beam batches over four targets.



The switchyard splits the 5MW proton beams in four parts





Y.Zou « The Accumulator Ring for the ESSnuSB Project», Nufact 2019

E. Bouquerel « Status of the Beam Switchyard for ESSnuSB», IPAC 2018

The ESSνSB Superbeam : The Target Station Facility

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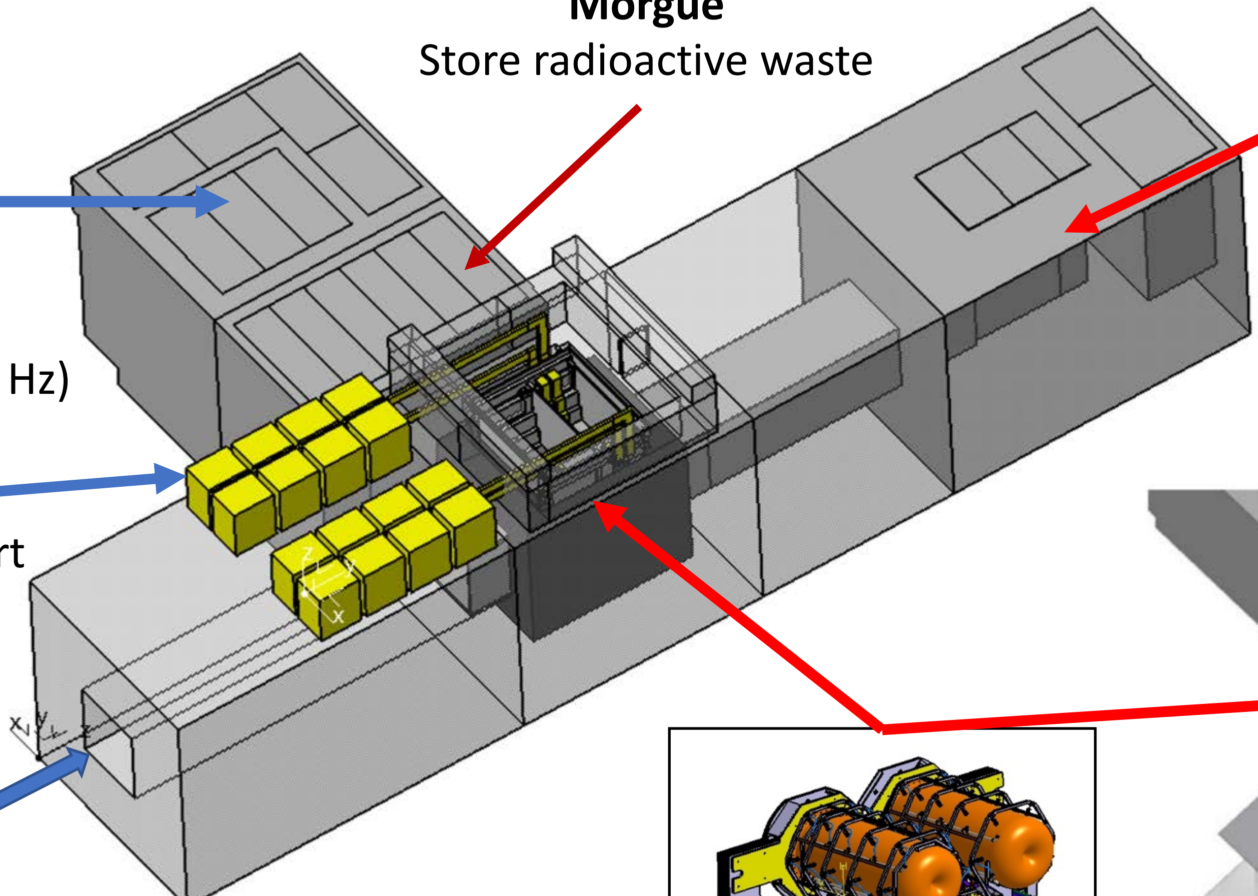
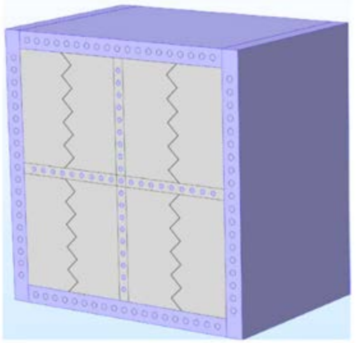
Hot Cell
- Able to manipulate/repair Hadron collector.
- Work under radioactive environment.

Power Supply Unit
- 16 modules (350 kA pulse/14 Hz)
- Located above the beam switchyard
- Outside of the radioactive part of the facility
- Good position to synchronize with switchyard PSU



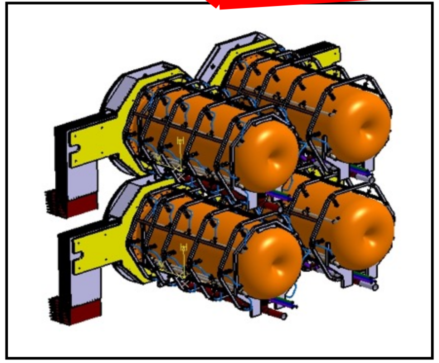
Morgue
Store radioactive waste

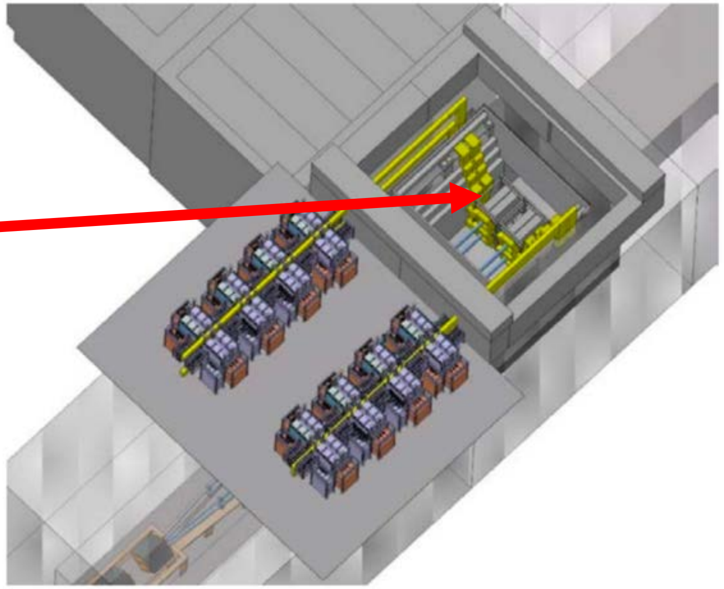
Beam Dump
(T.Tolba)



Proton Beam
4 x 1.25 MW

Hadronic Collector
Four Horn System





The ESSνSB Superbeam : The Packed Bed Target

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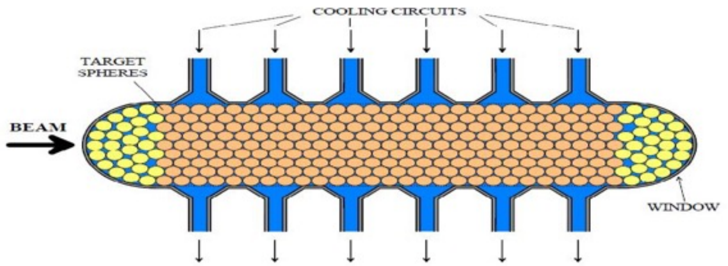
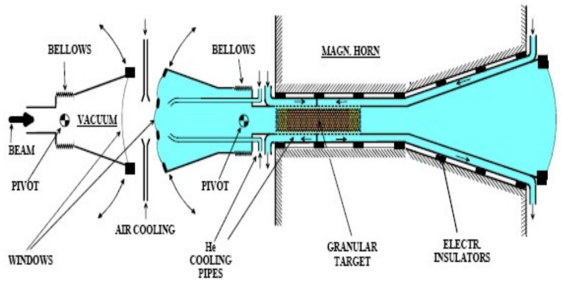
Production of the neutrino beam:

$\pi^+ \to \mu^+ + \nu_\mu$ (Positive mode)
$\pi^- \to \mu^- + \bar{\nu}_\mu$ (Negative mode)

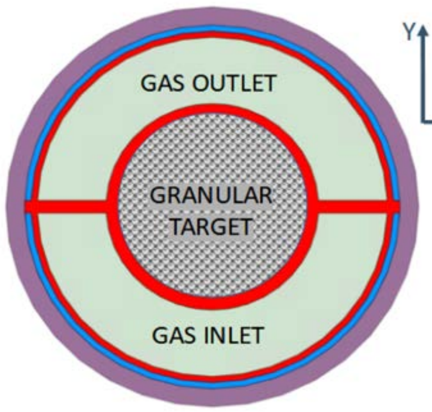
Concept packed bed target:



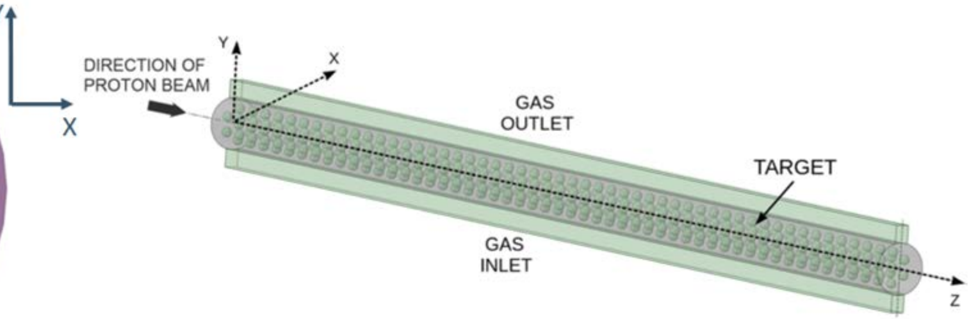
Cooling medium: water or gas helium



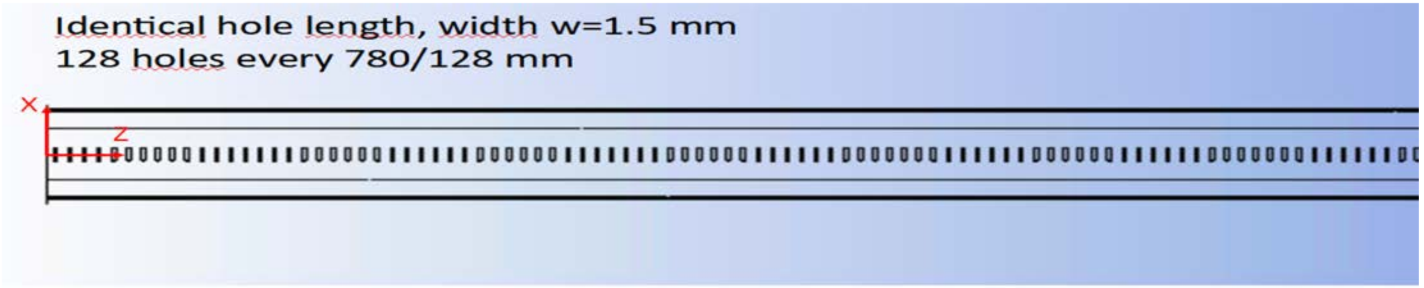
Concept of target integration inside a magnetic horn

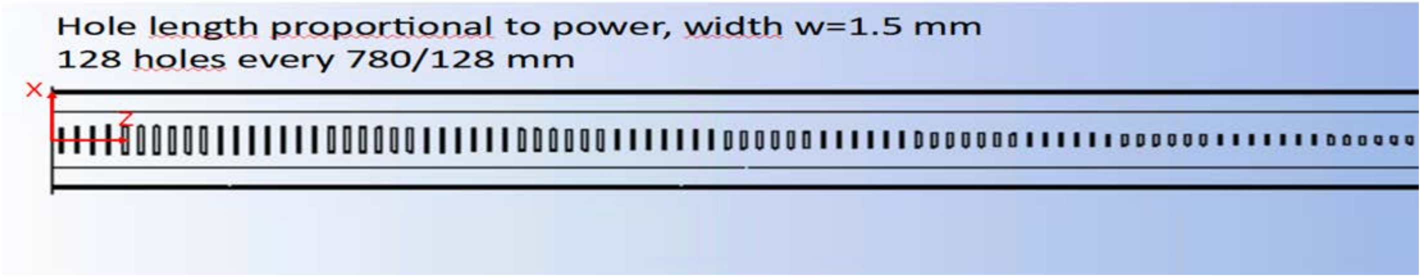


Cross-section of the target-horn integration system.



Simplified model of the granular target (Titanium Spheres 3 mm diameter, 66% packing Fraction)





Main conclusions (P. Sievers „A Stationary Target for the CERN-Neutrino-Factory", CERN-NuFact-Note 065):

ESS NEUTRINO SUPER BEAM

The ESSνSB Superbeam : The Packed Bed Target

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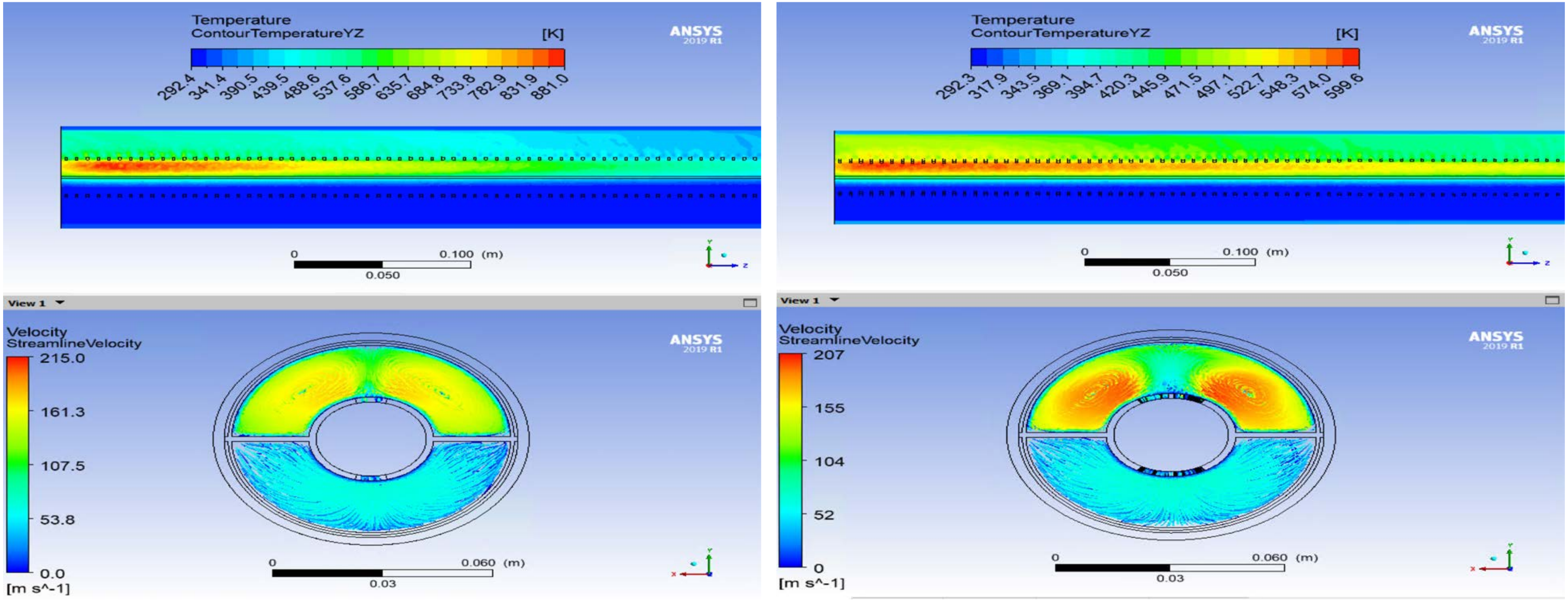

Temperature and velocity of helium inside the target-horn integrated system under the steady-state operation condition for the shell with standard (identical size) holes on the left and shell with optimized (proportional size) hole on the right.

The ESSνSB Superbeam : Horn Design Optimisation

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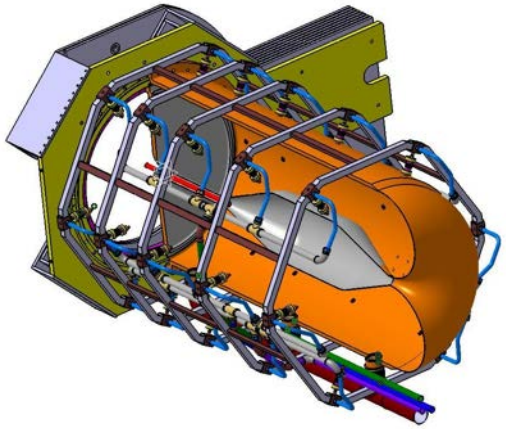
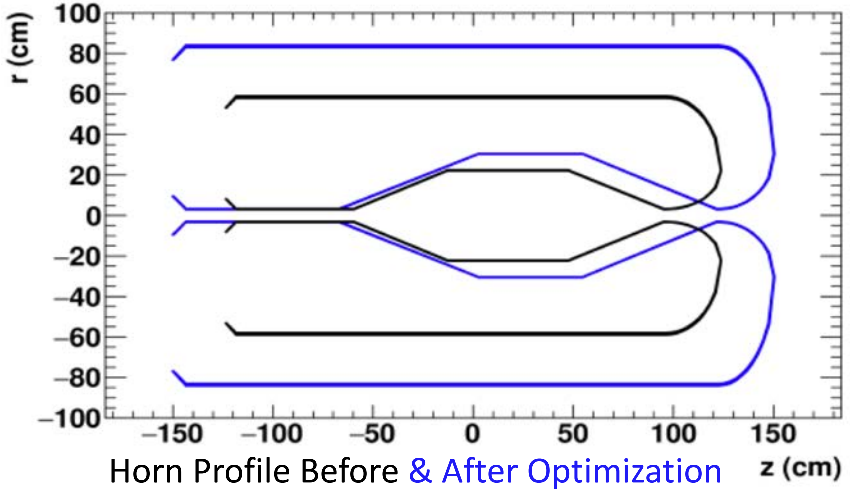
Design : MiniBooNe-Like Horn
Material : Aluminum Al T 6061 – T6
Geometry : Length 2.4 m – Diameter 1.2 m
Inner/Outer conductor thickness : 3 mm /10 mm
Peak Current : 350 kA

⇒ Conductors geometry fixed by GEANT4/FLUKA Simulation.

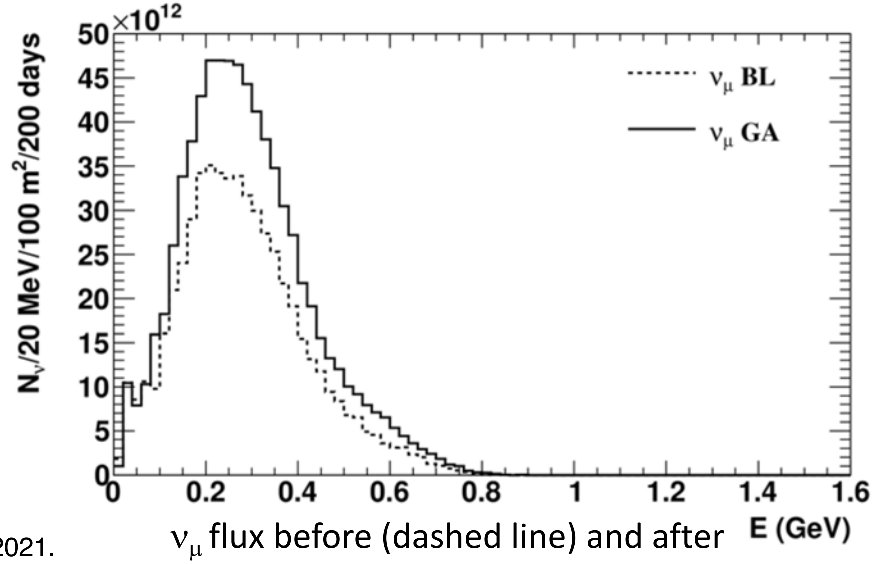




Horn Profile Before & After Optimization

Updated Design

- **An optimization study (Genetic Algorithm)** has been carried out, based on FLUKA simulations with different configurations of the magnetic horn and decay tunnel geometry [1,2].
- After the optimization study, it has been proposed to increase the length of the **decay tunnel from 25 m to 50 m.**
- The new geometry provides **higher statistics in the neutrino beam** and a consequent better performance of the experiment.
- Studies are currently on-going to verify the feasibility of the new horn in terms of thermomechanical stresses.



ν_μ flux before (dashed line) and after (continuous line) optimization

[1] L. D'Alessi et al. [ESSvSB], "Optimization of the Target Station for the ESSnSB Project Using the Genetic Algorithm", NeuTel Conference 2021.
[2] L. D'Alessi et al. [ESSvSB], "Neutrino Beam Optimization for the ESSnSB Experiment", International Research Network - Neutrino 2021

The ESSνSB Superbeam : Power Supply Unit

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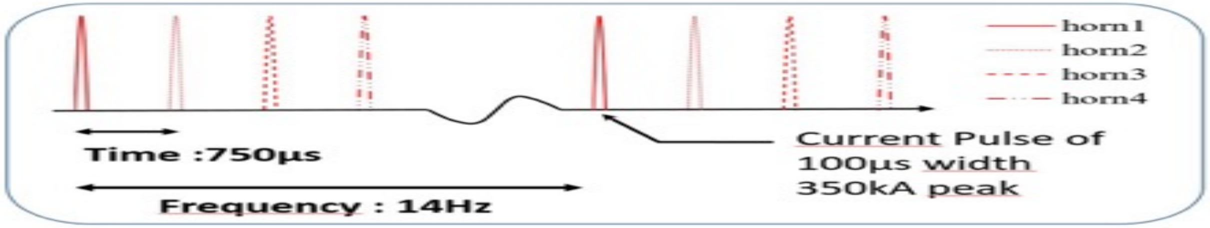
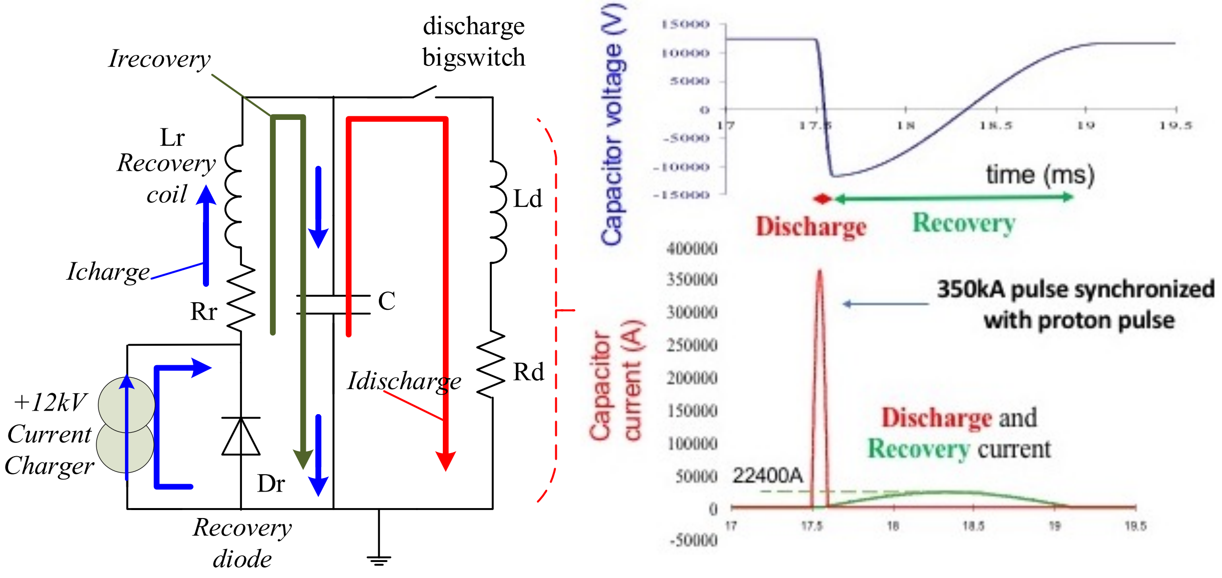
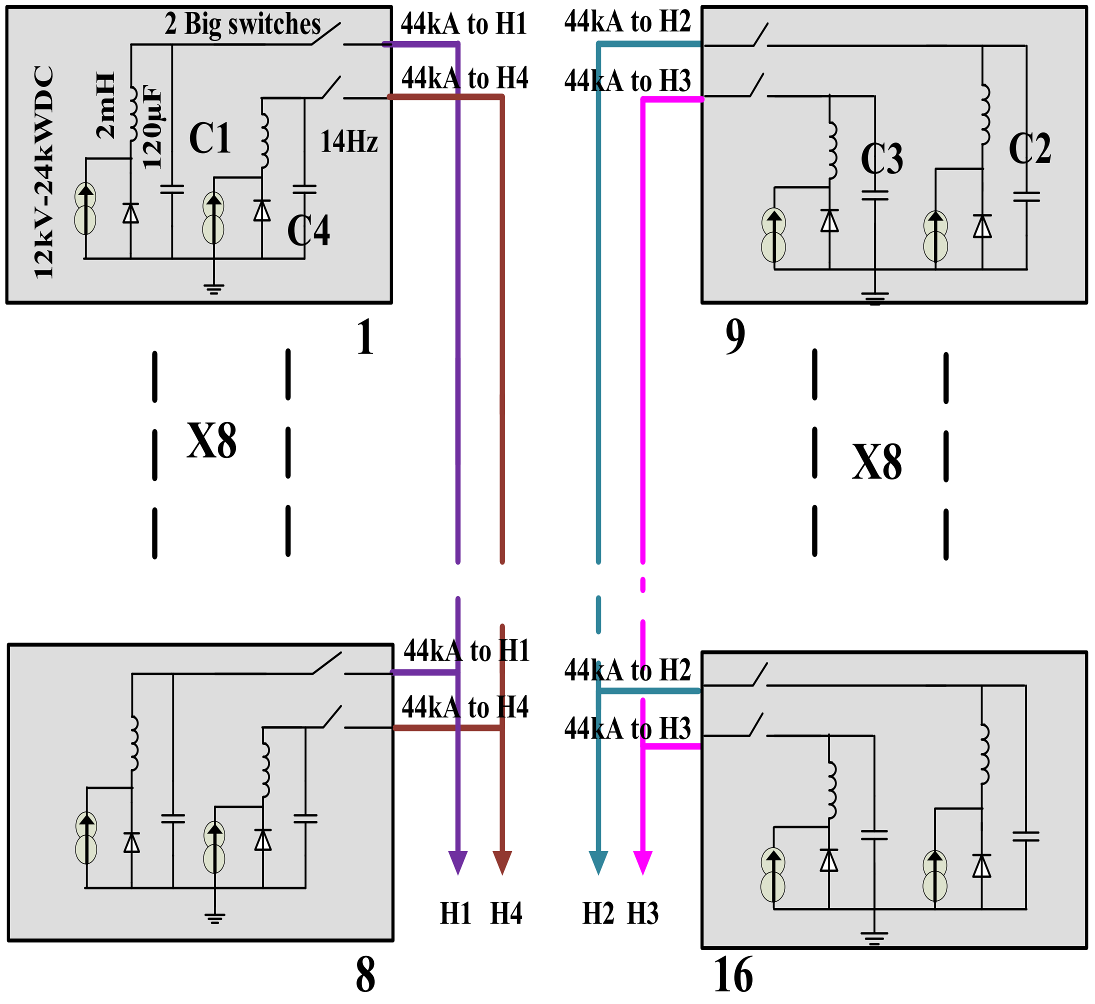
Each horn is pulsed by a half-sinusoid current waveform of 100 µs width and **350 kA peak current**, with a **very high RMS current of 9.3 kA**. The magnetic horn has a very low inductance of 0.9 µH and a low resistance.



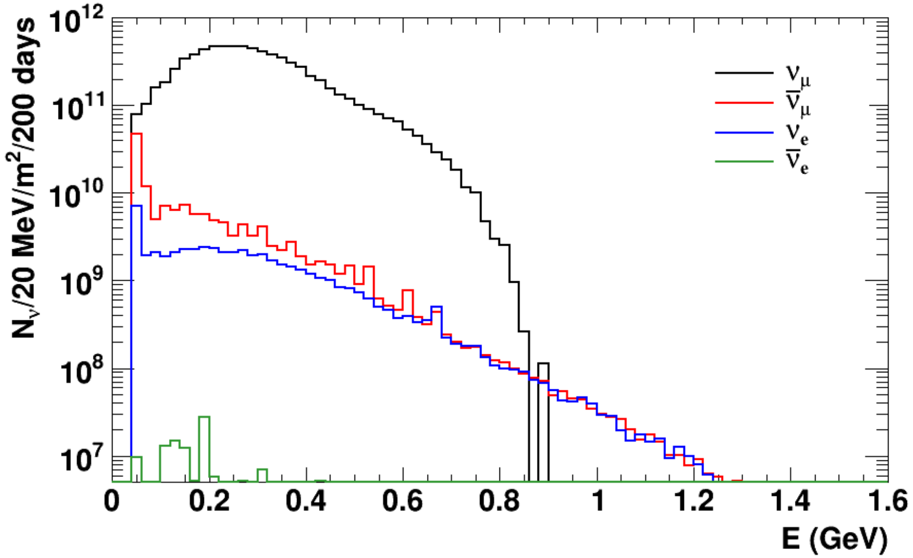




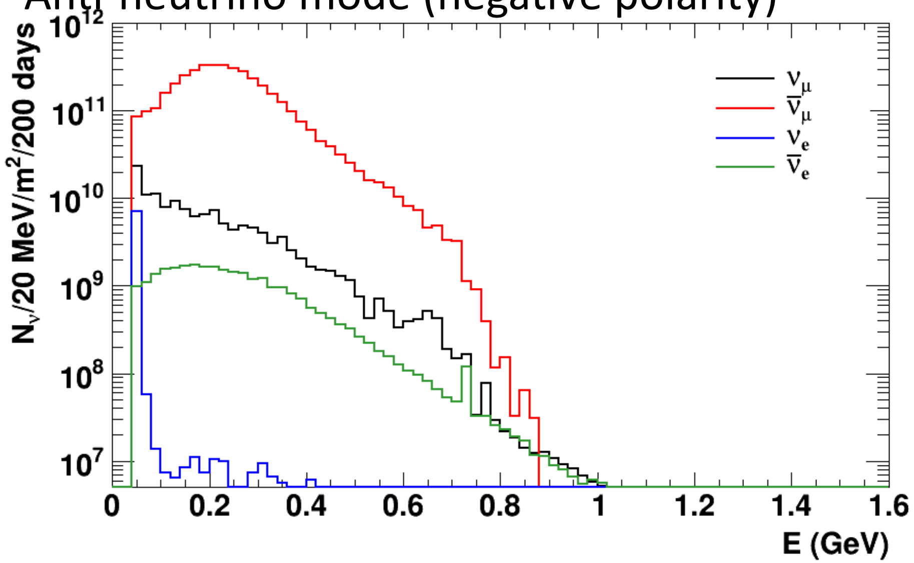
ESSvSB 4X350 kA PSU made with 16 modules, 2X44 kA each.

The ESSνSB Superbeam : Neutrino fluxes

Neutrino mode (positive polarity)



Anti-neutrino mode (negative polarity)



- Almost pure ν_μ beam
- Small ν_e contamination which could be used to measure ν_e cross-sections in a near detector

	Positive		Negative	
	$N_\nu\ (10^{10}/m^2)$	%	$N_\nu\ (10^{10}/m^2)$	%
ν_μ	743	97.4	13.7	3.3
$\bar{\nu}_\mu$	14.5	1.9	397	95.9
ν_e	5.2	0.7	0.7	0.02
$\bar{\nu}_e$	0.01	0.002	2.7	0.7

at 100 km from the target and per year (in absence of oscillations)

The ESSνSB Superbeam : Near & Far Detector

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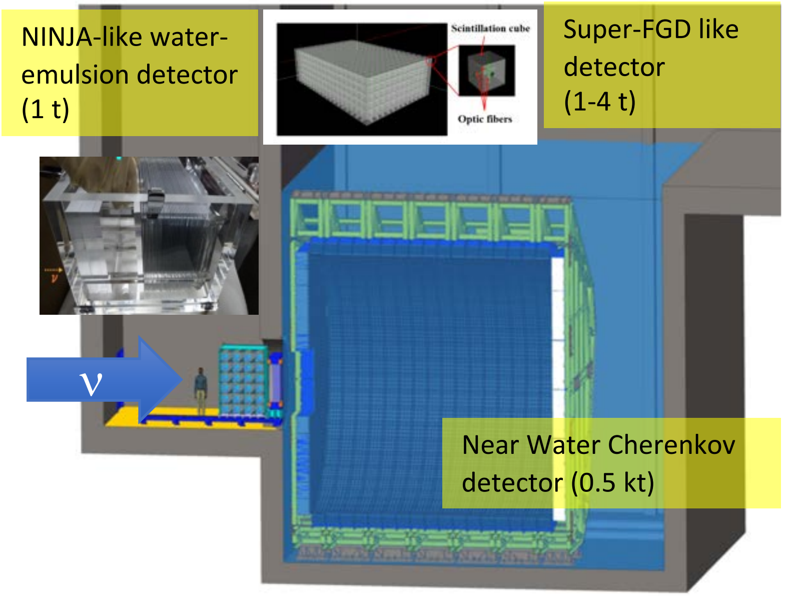
Near Detector

- 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[1] experiment, upstream of the SFGD, for cross-section measurements.



Far Detector

- 538 kt fiducial volume (~10xSuperK)
- Readout 20" PMTs (40% optical coverage)
- Event reconstruction with fiTQun [2,3]
- New migration matrices obtained

Can also be used for other purposes: Proton decay, astroparticles, Galactic SN , Supernovae "relics", Solar Neutrinos, Atmospheric Neutrinos

WC type detector

[1] A. Hiramoto et al., Phys. Rev. D 102, 072006 (2020), arXiv:2008.03895.
[2] T2K Collaboration, A. D. Missert, J. Phys. Conf. Ser. 888 (2017), no. 1 012066
[3] Super-Kamiokande Collaboration, M. Jiang et al., PTEP 2019 (2019), no. 5 053F01, [arXiv:1901.03230].

The ESSνSB Superbeam : Sensitivity & Precision

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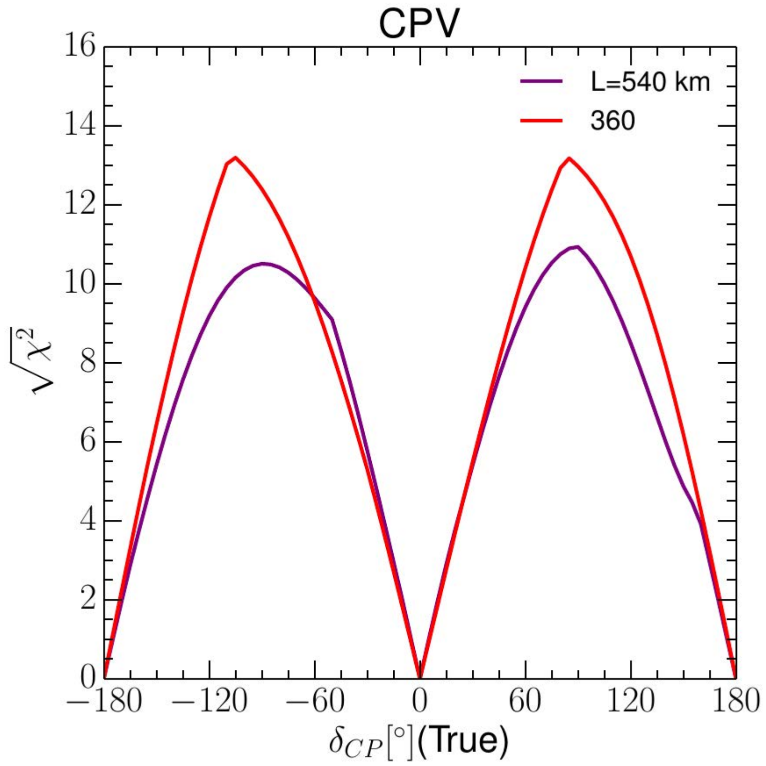
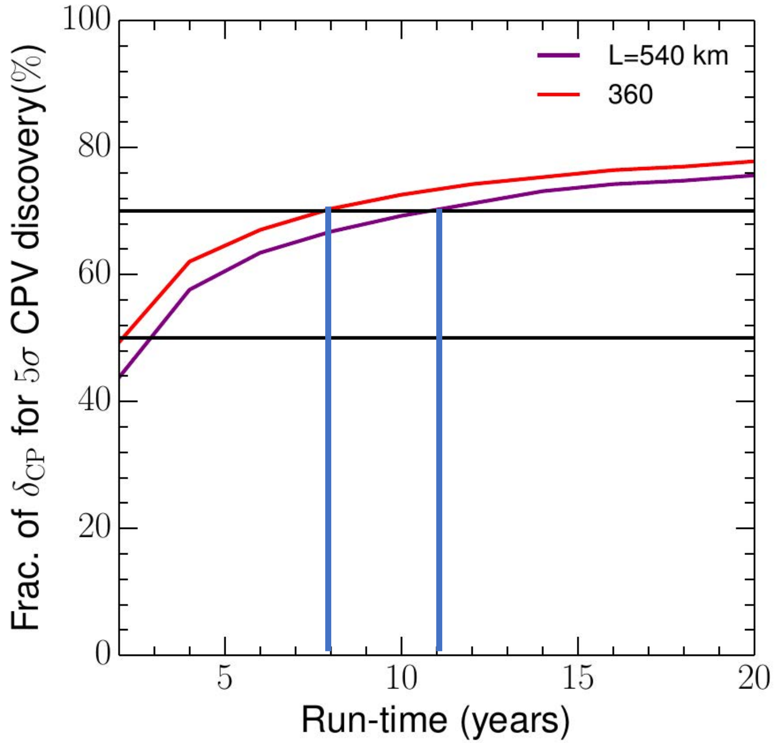
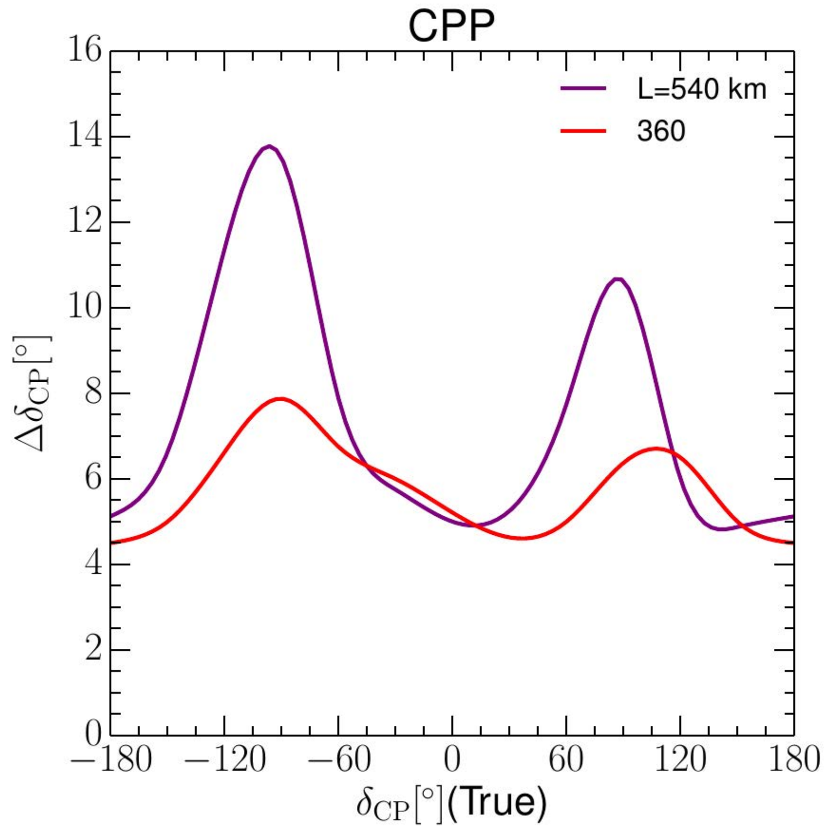


Sensitivity for $\delta_{CP} = \pm \pi/2$:
11 σ (540 km)
13 σ (360 km)



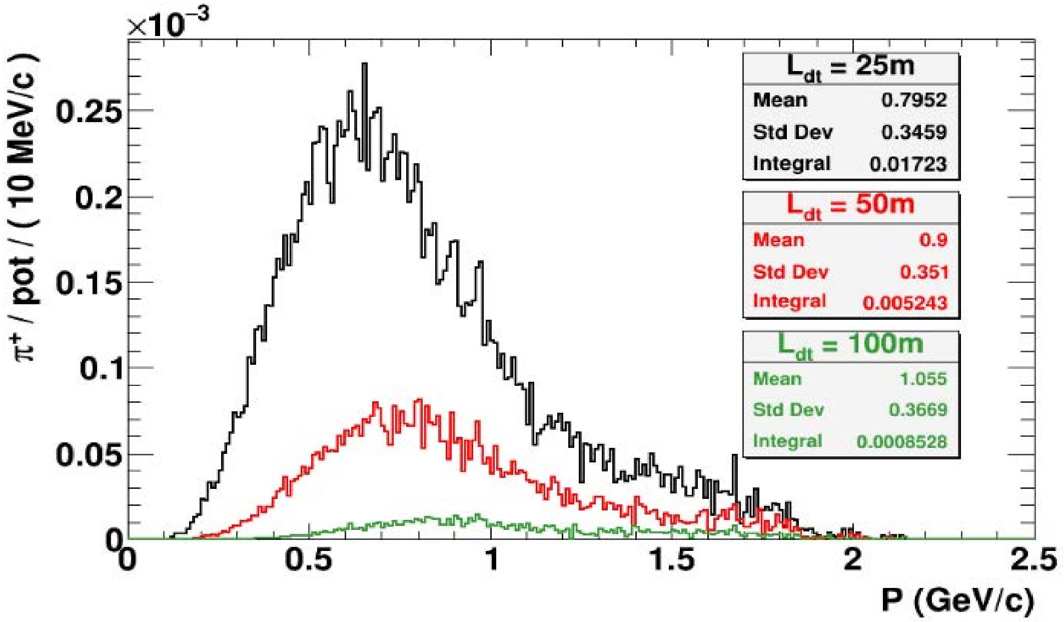
75% δ_{CP} coverage @ 5 σ:
11 years (540 km)
6 years (360 km)

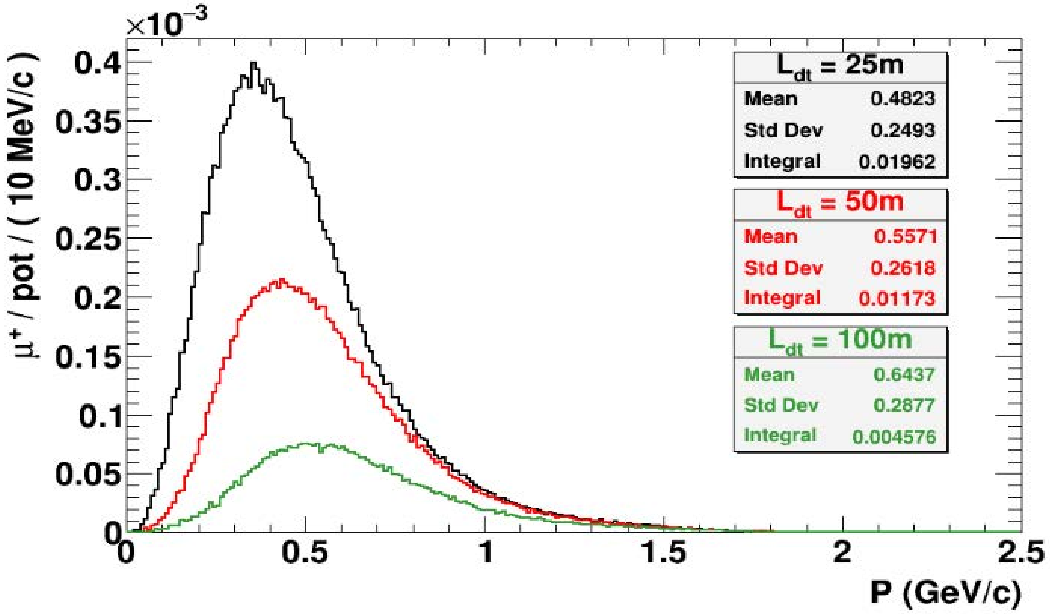


High precision of δ_{CP} measurement

From: A. Alekou et Al « **Updated physics performance of the ESSnuSB experiment** » [arXiv:2107.07585]

Acceptance 4m x 4m





$L_{dt}\,(m)$	$N_\pi\ (\pi^+/pot)$	$N_\pi\ (\pi^+/s)$	$N_\pi\ (\pi^+/200d)$	$\langle P_\pi\rangle\,(GeV/c)$
25	0.017	2.1×10^{14}	3.7×10^{21}	0.79
50	5×10^{-3}	0.6×10^{14}	1.1×10^{21}	0.9
100	8.5×10^{-4}	0.1×10^{14}	0.2×10^{21}	1.06

$L_{dt}\,(m)$	$N_\mu\ (\mu^+/pot)$	$N_\mu\ (\mu^+/s)$	$N_\mu\ (\mu^+/200d)$	$\langle P_\mu\rangle\,(GeV/c)$
25	0.02	2.5×10^{14}	4.3×10^{21}	0.48
50	0.01	1.2×10^{14}	2.1×10^{21}	0.56
100	4.5×10^{-3}	0.6×10^{14}	1.0×10^{21}	0.64

From: L. D’Alessi (HEP-EPS2021)

The ESSνSB Superbeam : Future Possibilities

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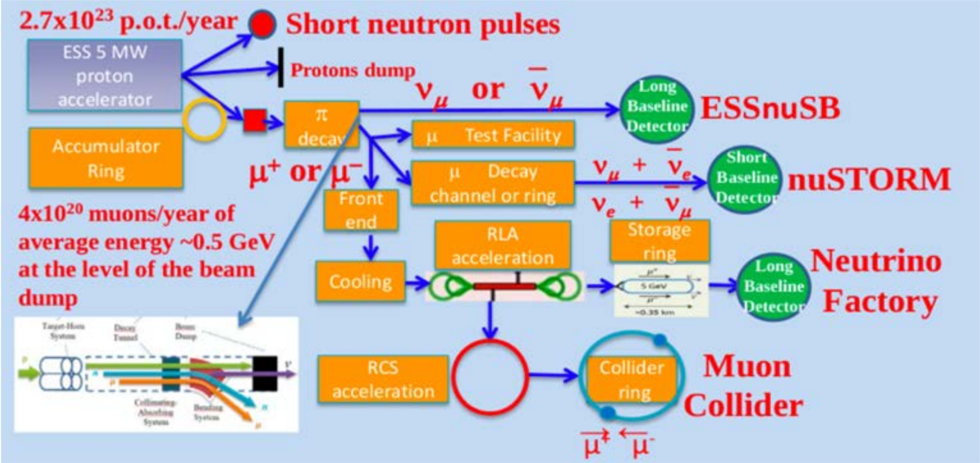
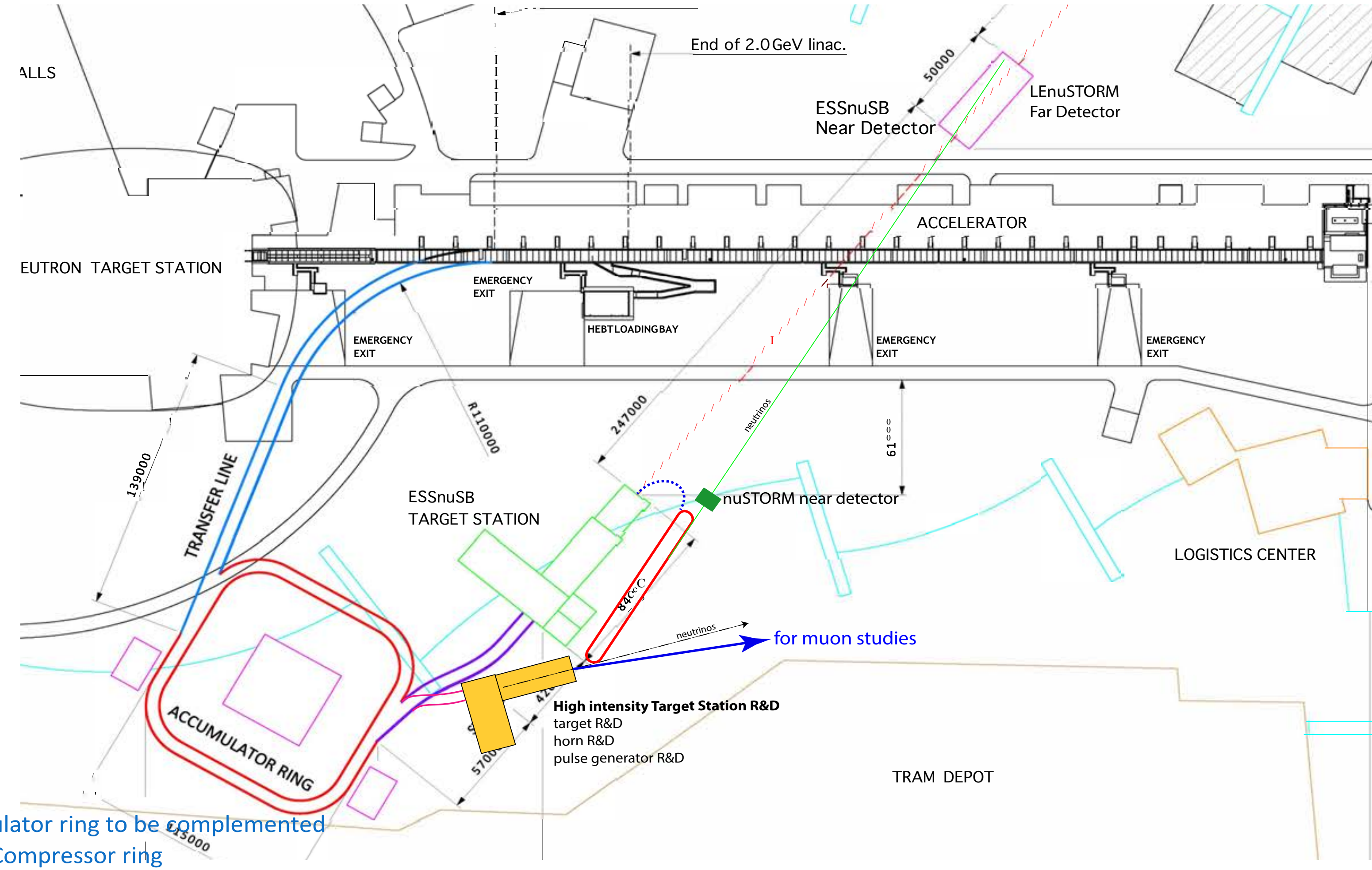


Several proposals have been discussed during the first HIFI (High Intensity Frontier Initiative) workshop held in Uppsala (02-03.03.2020):

- ESSνSB
- Muon Collider R&D
- Short-pulse Neutron Physics
- nuSTORM
- Neutrino Factory
- Neutrinos from Decay at Rest
- Coherent Elastic Neutrino Nucleus Scattering (CEνNS)

https://indico.cern.ch/event/849674/



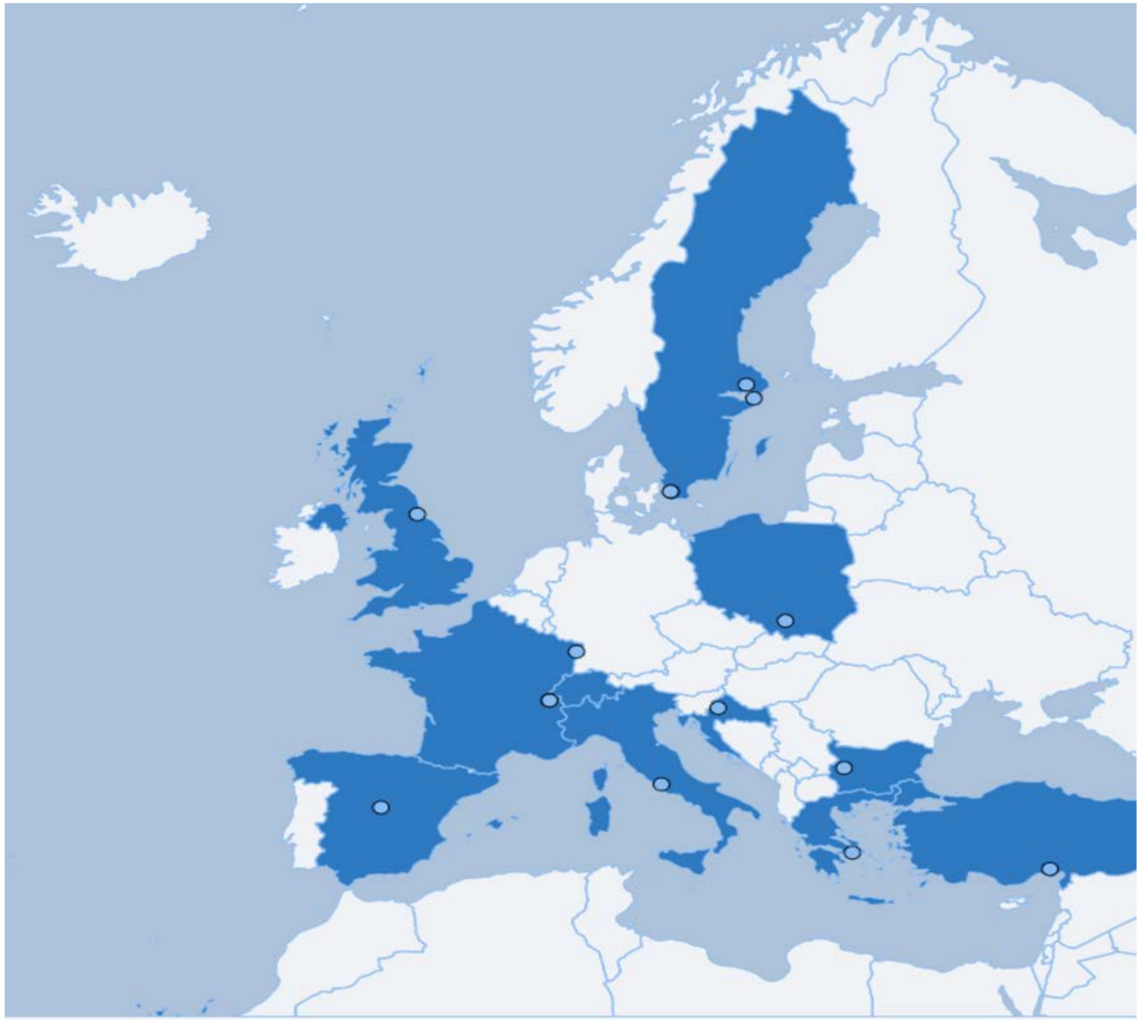
Accumulator ring to be complemented with a Compressor ring

See : « Introduction of the ESSnuSB/HIFI Design Study program 2022-2025 » M. Dracos (Nufact 2021)

Outlines:

- The proposed design for the ESSνSB represents **an unique opportunity to have a Neutrino Superbeam in Europe**.
- **Recent optimizations** predict that in 10 years of data taking ESSnuSB will be able to reach 5 σ over 75% of δ_{CP} range
- Through the "High Intensity Frontier Initiative" workshop, the capability of the European Spallation Source has been discussed to **a rich complementary physics program**.
- A R&D phase is necessary to prepare the future.
- Synergies with other facilities can interest more people.
- Prepare next European calls.

Website : https://essnusb.eu/



Map of the European contributions

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