Modifications on ESS for neutrino Super Beam

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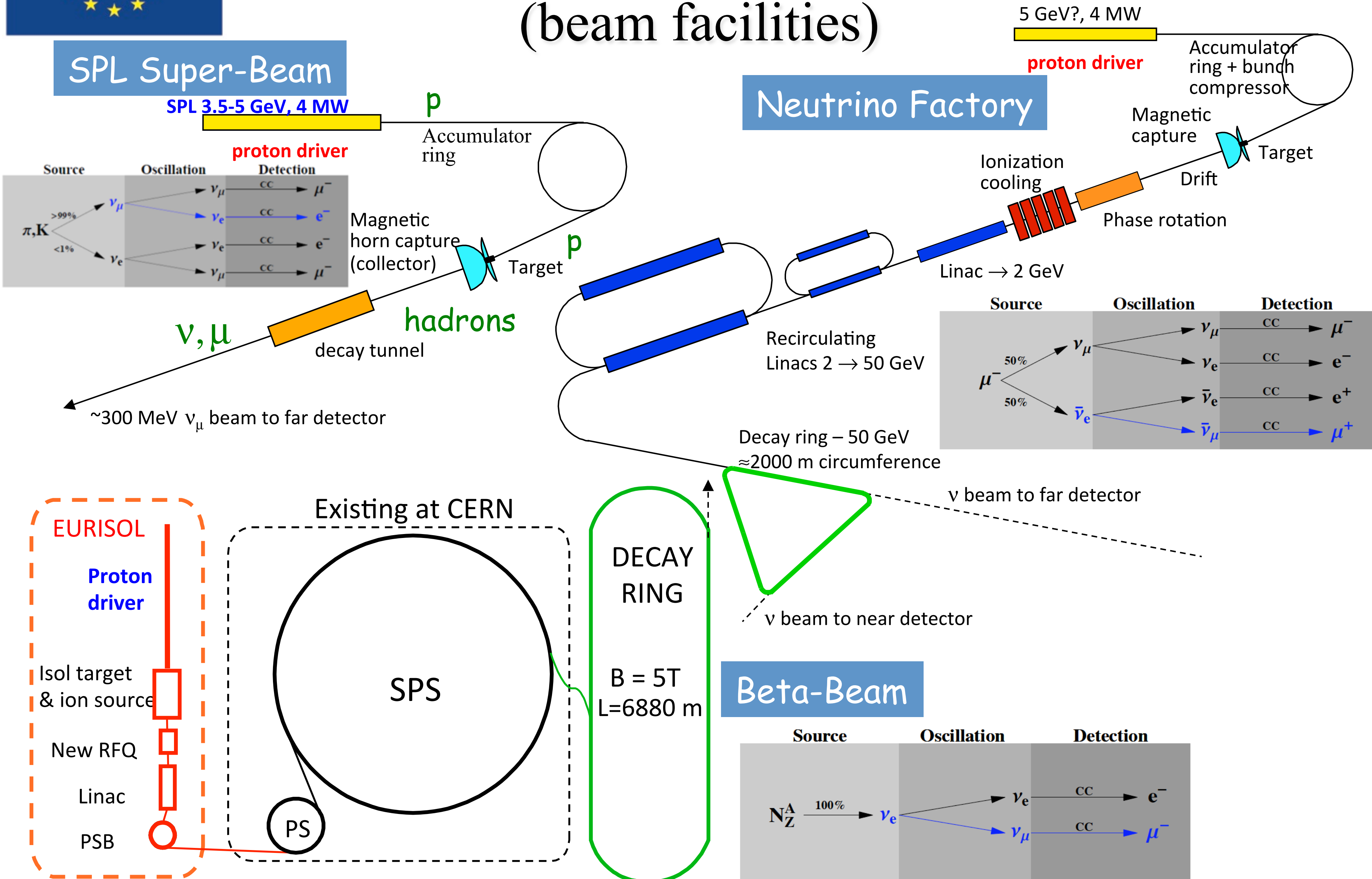
(E. Wildner, T. Ekelof)

EUROnu Projects
(beam facilities)

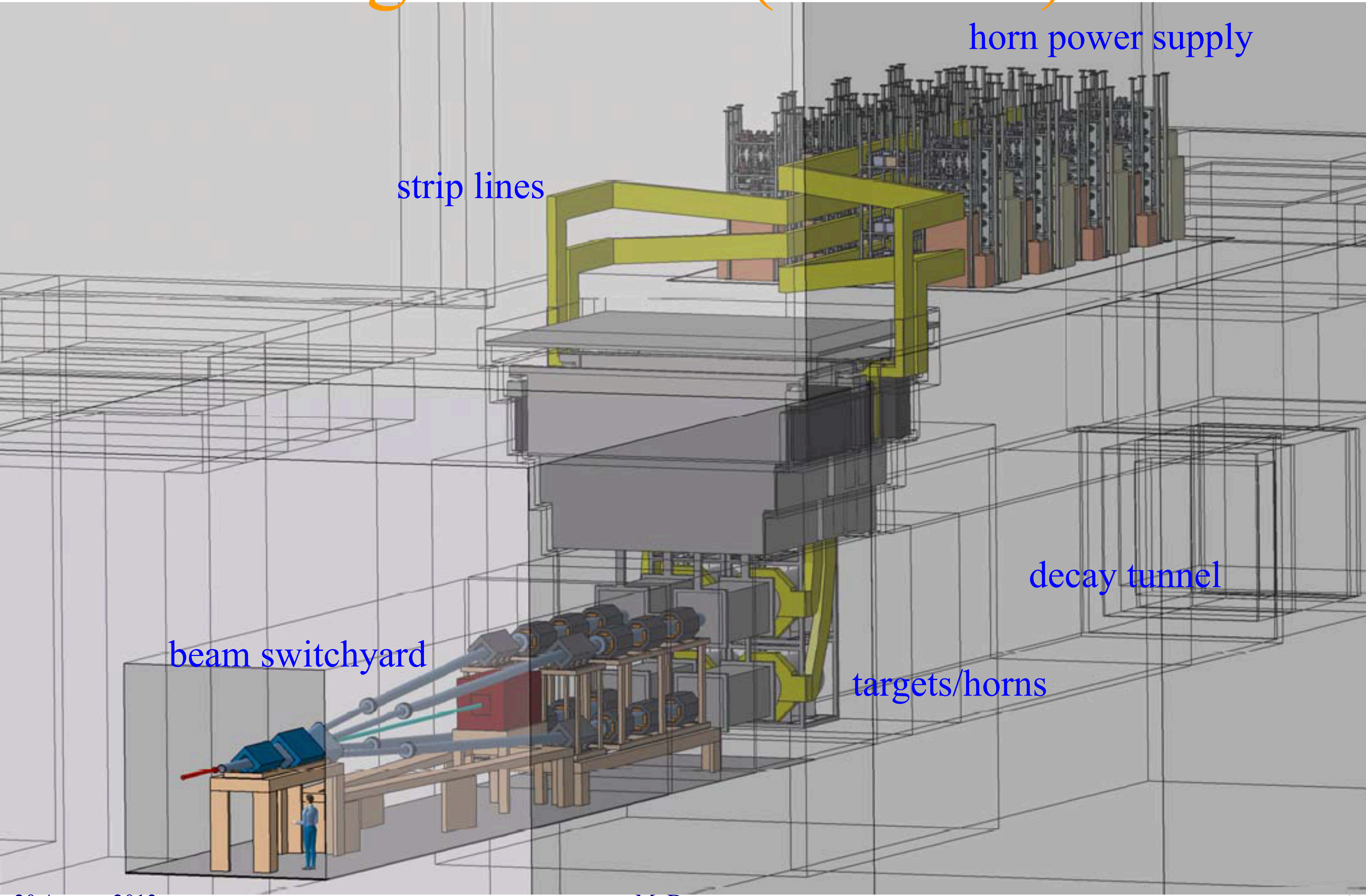


^{6}He for ν_e and ^{18}Ne for $\bar{\nu}_e$

European Long Baseline Super Beam Projects

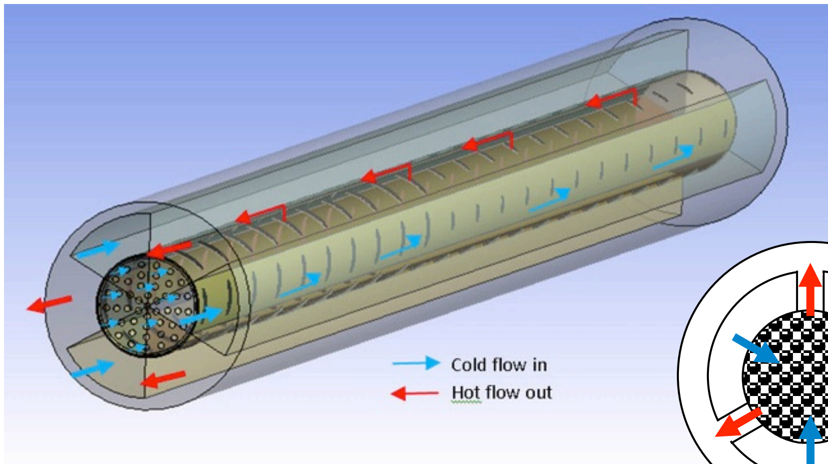
Studied by LAGUNA

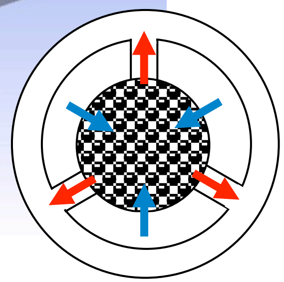
Target Station (EUROν)

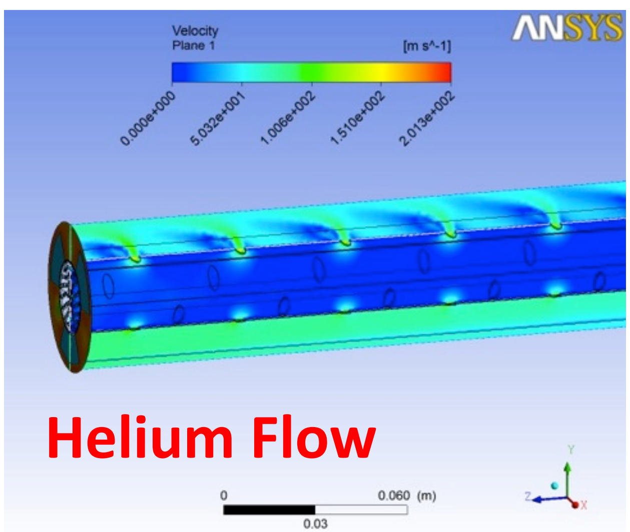


4-Target/Horn system (EUROnu)

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







<u>Helium Velocity</u>

Maximum flow velocity = 202m/s

Maximum Mach Number < 0.2

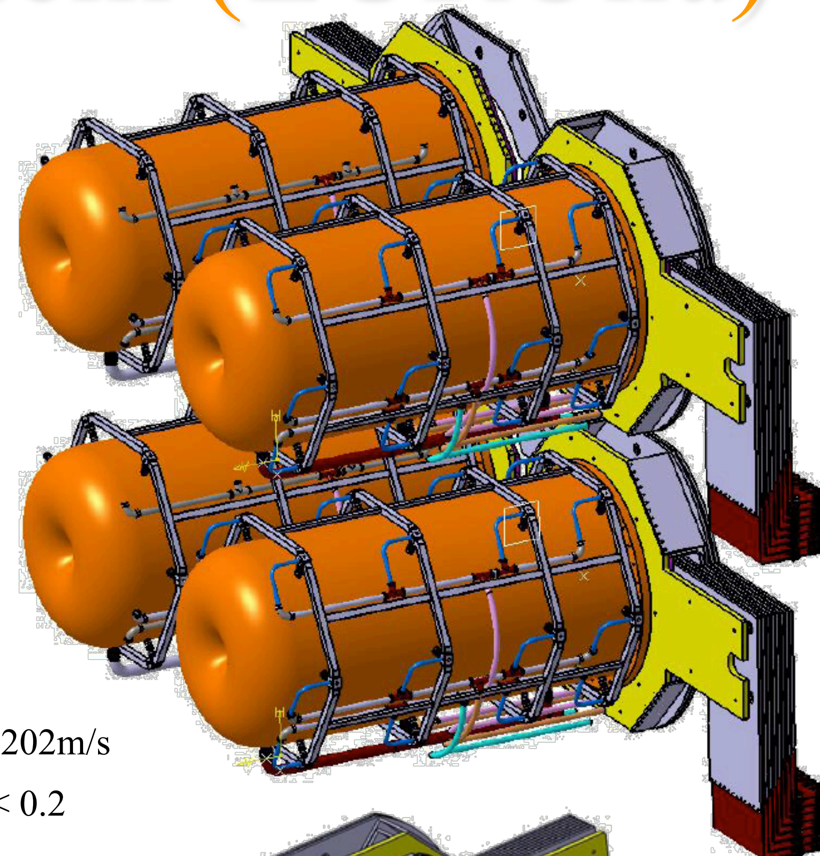
<u>Helium Gas Temperature</u>

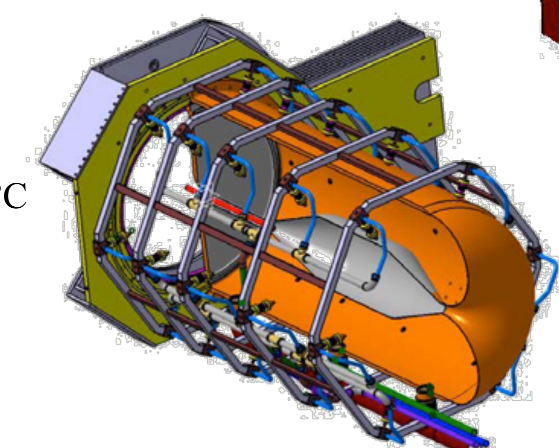
Total helium mass flow = 93 gr/s

Maximum Helium temperature = 584°C

Helium average outlet Temperature = 109°C

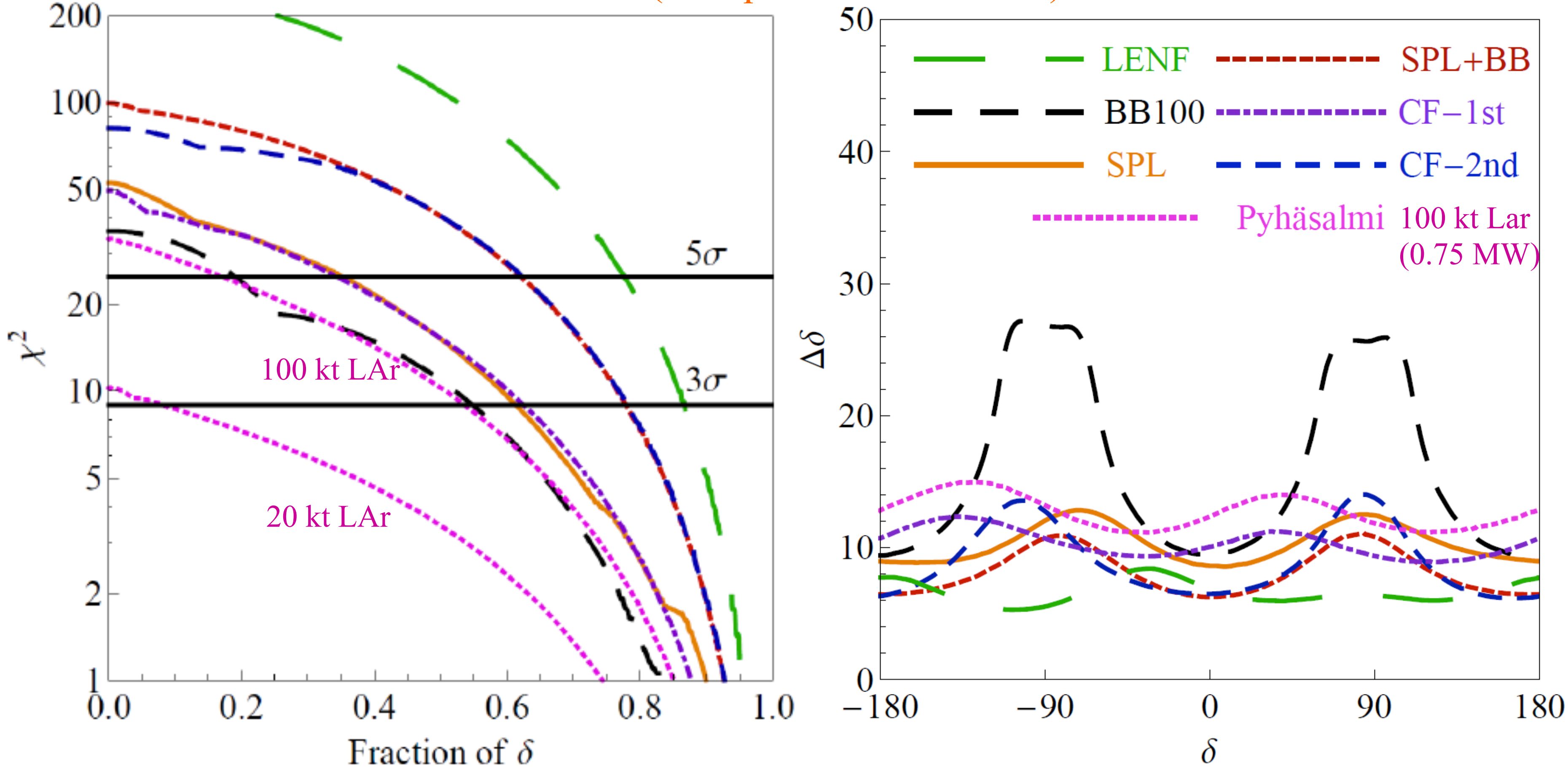
First tests with beam in the new HiRadMat@SPS facility at CERN in 2014





Physics Performance (CPV)

(Enrique Fernantez et al.)



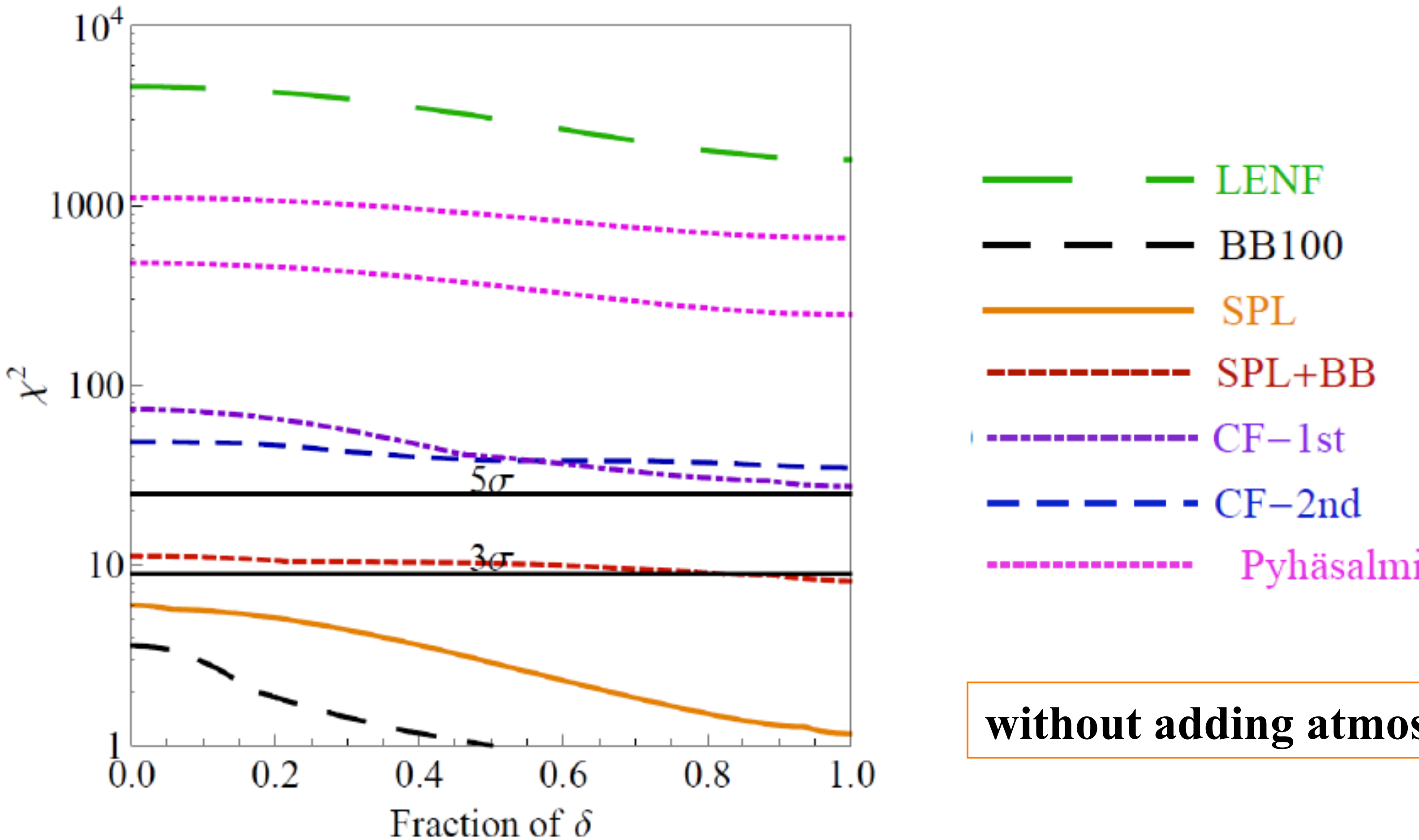
- SPL: CERN to Fréjus (130 km)
- CF-1st: CERN to Canfranc (650 km) 1st max.
- CF-2nd: CERN to Canfranc 2nd max.

1 Mton WC detector (440 kton fiducial), 5%/10% syst.

- Solar sector $\begin{cases} \Delta m^2_{21} = 7.62^{+0.19}_{-0.19} \cdot 10^{-5} \mathrm{eV}^2 \\ \sin^2\theta_{12} = 0.320^{+0.015}_{-0.017} \end{cases}$
- Atm. sector $\begin{cases} \Delta m^2_{31} = 2.53^{+0.08}_{-0.10} \cdot 10^{-3} / -2.40^{+0.10}_{-0.07} \cdot 10^{-3}\ \mathrm{eV}^2 \\ \sin^2\theta_{23} = 0.49^{+0.08}_{-0.05} / 0.53^{+0.05}_{-0.07} \end{cases}$

$$\sin^2\theta_{13} = 0.026^{+0.003}_{-0.004} / 0.027^{+0.003}_{-0.004}$$

Physics Performance (MH)



without adding atmospherics

- SPL: CERN to Fréjus (130 km)
- CF-1st: CERN to Canfranc (650 km) 1st maximum
- CF-2nd: CERN to Canfranc 2nd maximum

1 Mton WC detector (440 kton fiducial), 5%/10% syst.

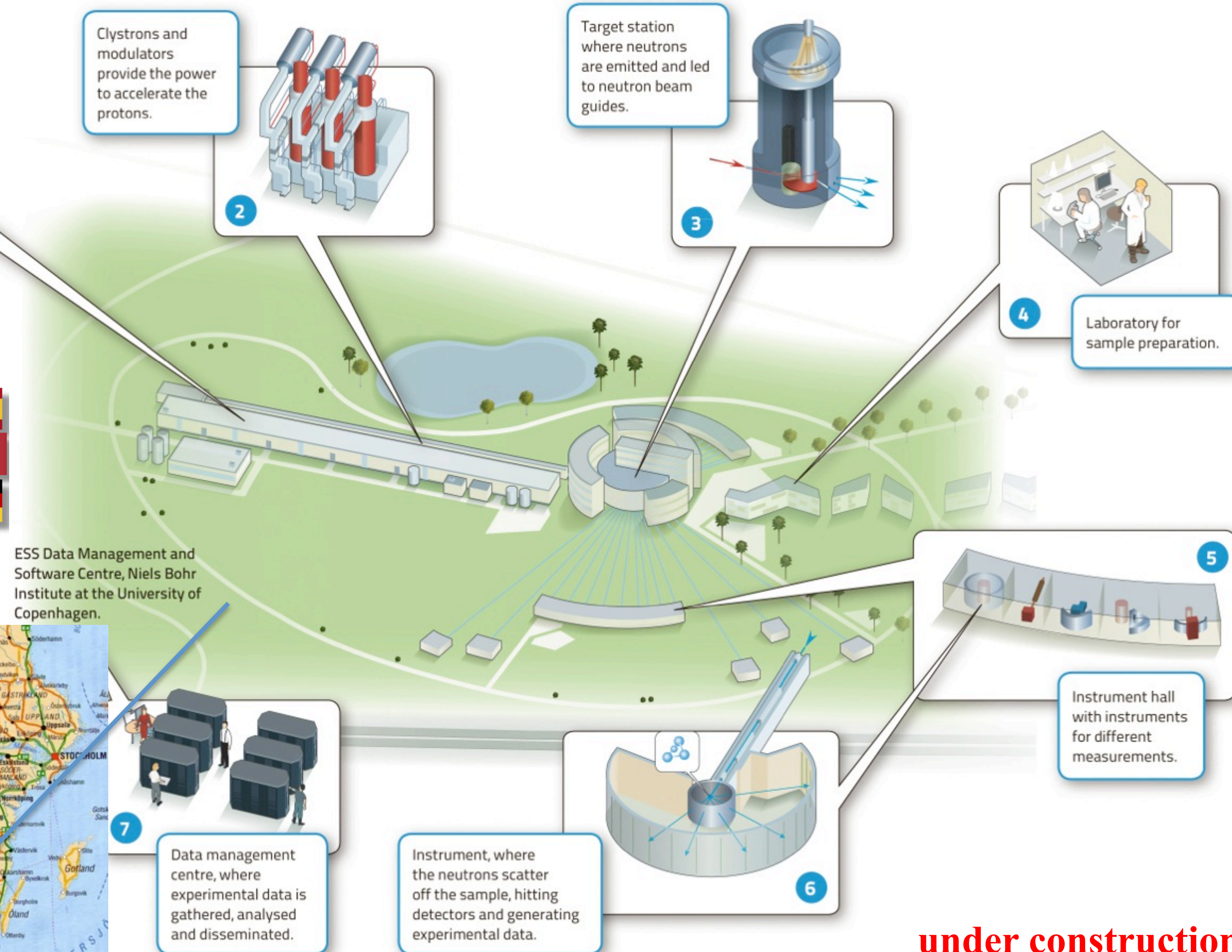
SPL not any more part of LHC upgrades

Any other intense proton source in Europe?

(in the context of European Strategy for Particle Physics)

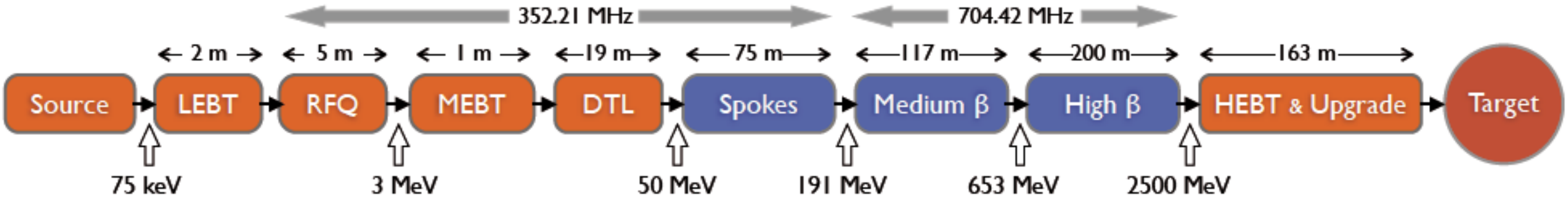
f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading neutrino projects in the US and Japan.

European Spallation Source

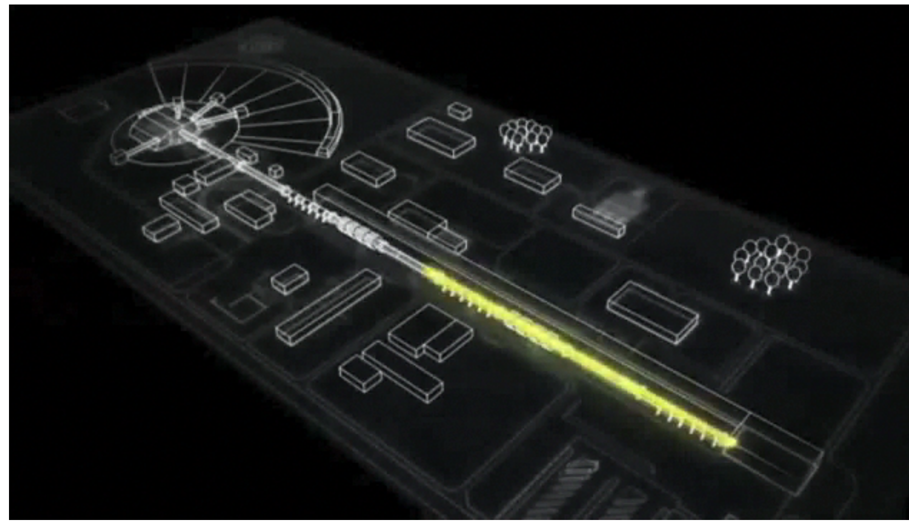


under construction (~1.5 B€ facility)

ESS proton linac



- The ESS will be a copious source of spallation neutrons
- 5 MW average proton beam power
- 125 MW peak power
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons)
- 4% duty factor
- linac mostly (>97%) superconducting
- 2.5 GeV protons (up to 3.0 GeV with linac upgrades)
- **>2x10^{23} p.o.t/year**



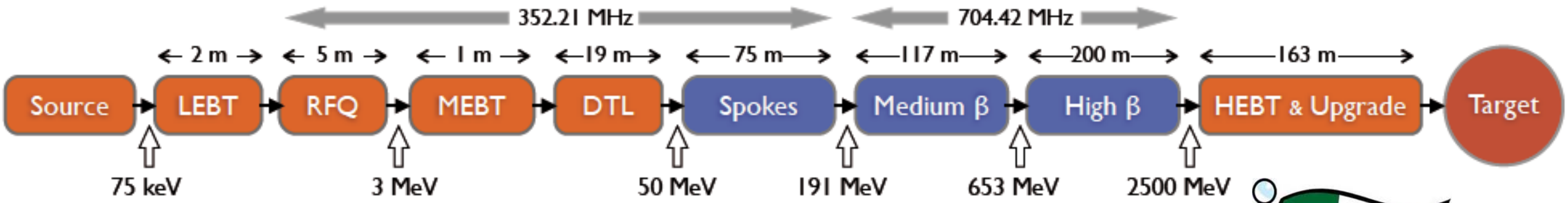
System	Energy MeV	Freq. MHz	β_{Geo}	No. of Md./Cv.*	Length m
Source	0.075	–	–	–	2.5
LEBT	0.075	–	–	–	1.6
RFQ	3	352.21	–	1	4.7
MEBT	3	352.21	–	2	1.0
DTL	50	352.21	–	3	19
Spokes	188	352.21	0.57	14 / 28	58
Low β	606	704.42	0.70	16 / 64	108
High β	2506	704.42	0.90	15 / 120	196

ESS parameters

Parameter	Unit	Value	
Average beam power	MW	5	
Number of target stations		1	
Number of instruments in construction budget		22	
Number of beam ports		48	
Number of moderators		2	
Separation of ports	degrees	5	
Proton kinetic energy	GeV	2.5	→ 2 GeV at the beginning
Average macro-pulse current	mA	50	→ 62.5
Macro-pulse length	ms	2.86	
Pulse repetition rate	Hz	14	
Maximum accelerating cavity surface field	MV/m	40	
Maximum linac length (without 100 m upgrade space)	m	482.5	→ enough to go up to 3 GeV
Annual operating period	h	5000	
Reliability	%	95	→ 198 days

ESS Technical Design Report
April 23, 2013
ESS-doc-274
http://europeanspallationsource.se/documentation/tdr.pdf

Linac Sharing



- **Ion source** : Istituto Nazionale di Fisica Nucleare (INFN) – Catania, **Italy**

- **Radio Frequency Quadrupole (RFQ)**: Commissariat à l'énergie atomique (CEA) – Saclay, **France**
- **Medium Energy Beam Transport (MEBT)**: ESS-Bilbao, **Spain**

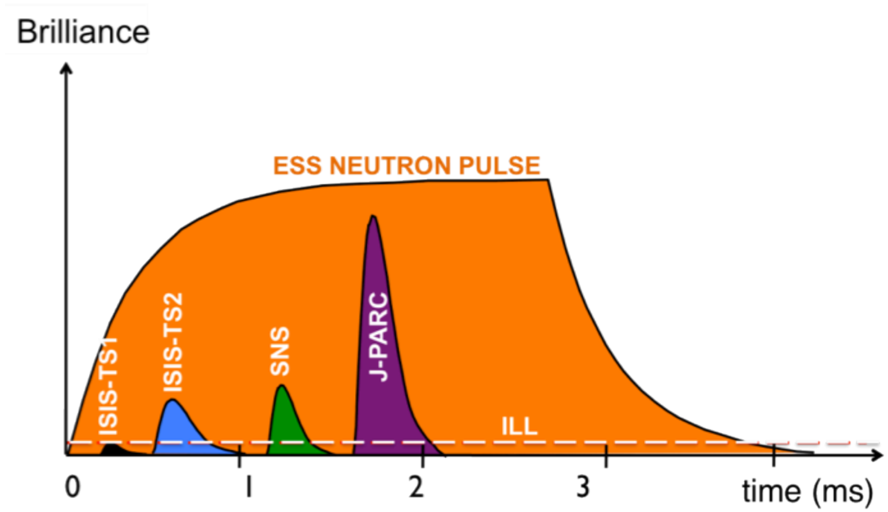
- **Drift tube Linac (DTL)**: Istituto Nazionale di Fisica Nucleare (INFN) – Legnaro, **Italy**
- **Spoke cavities**: Institut de Physique Nucléaire (CNRS) – Orsay, **France**

- **Elliptical cavities**: Commissariat à l'énergie atomique (CEA) – Saclay, **France**
- **High Energy Beam Transport**: Aarhus University, **Denmark**

- **Spoke RF sources**: Uppsala University, **Sweden**
- **RF regulation**: Lund University, **Sweden**

What is different from SNS?

- The average proton beam power will be 5 MW
  - Average neutron flux is proportional to average beam power
  - 5 MW is five times greater than SNS beam power
- The total proton energy per pulse will be 360 kJ
  - Beam brightness (neutrons per pulse) is proportional to total proton energy per pulse
  - 360 kJ is over 20 times greater than SNS total proton energy per pulse



Well defined ESS Schedule

2010 - ESS Company set up

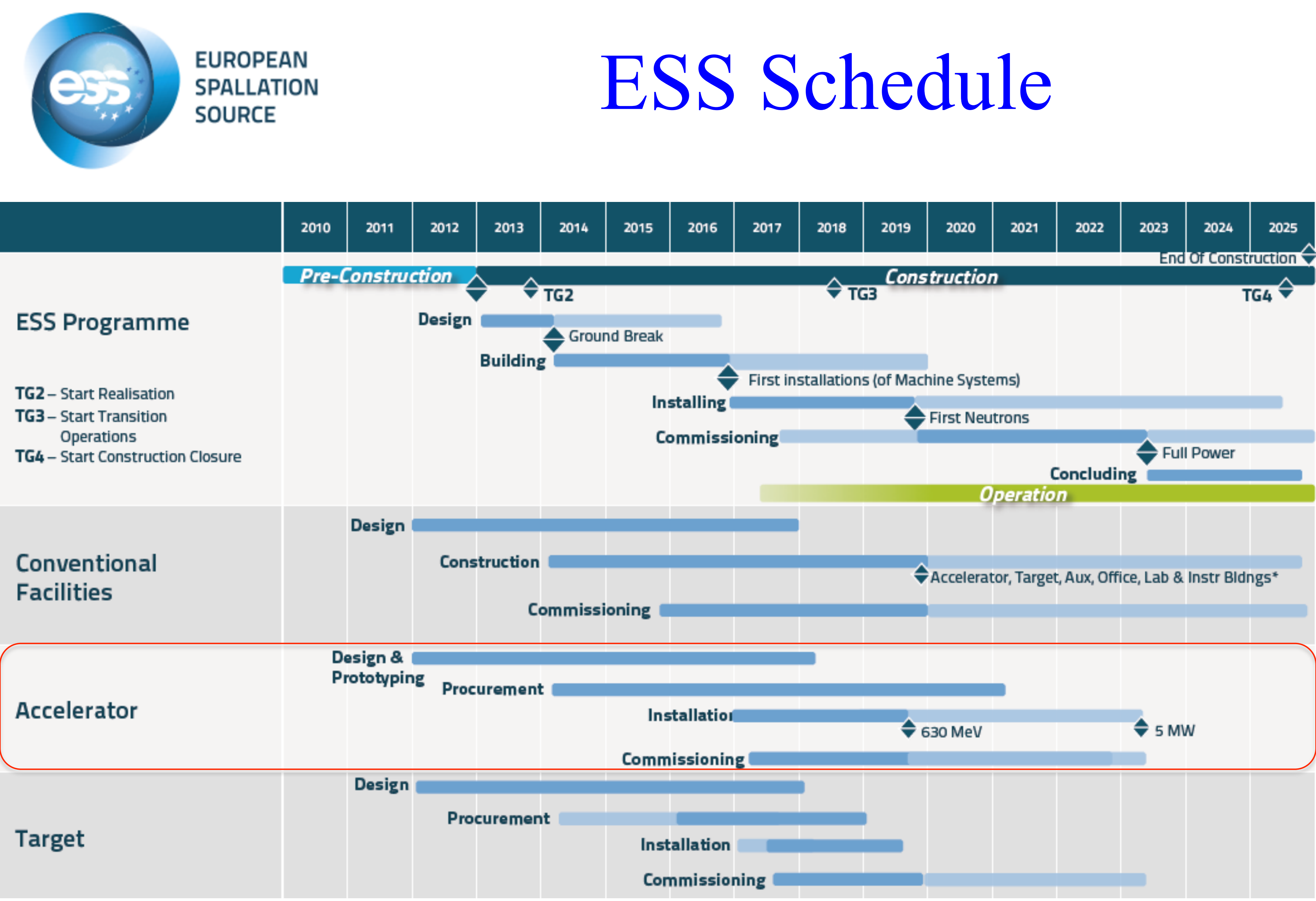
2010 - 2012 **Technical Design Review**
2010 - 2012 **Pre-Construction & Site Planning**
2009 - 2012 **Licensing and Planning**
2010 - 2012 **Finalisation of international negotiations**

2013 - 2019 **Construction Phase - 7 instruments**
2019 - 2025 **Completion Phase - all 22-33 instruments in place**

2026 - 2066 **Operations Phase**
2066 – 2071 **Decommissioning Phase**

- 1st beam before the end of the decade
- 5 MW by 2023

ESS Schedule

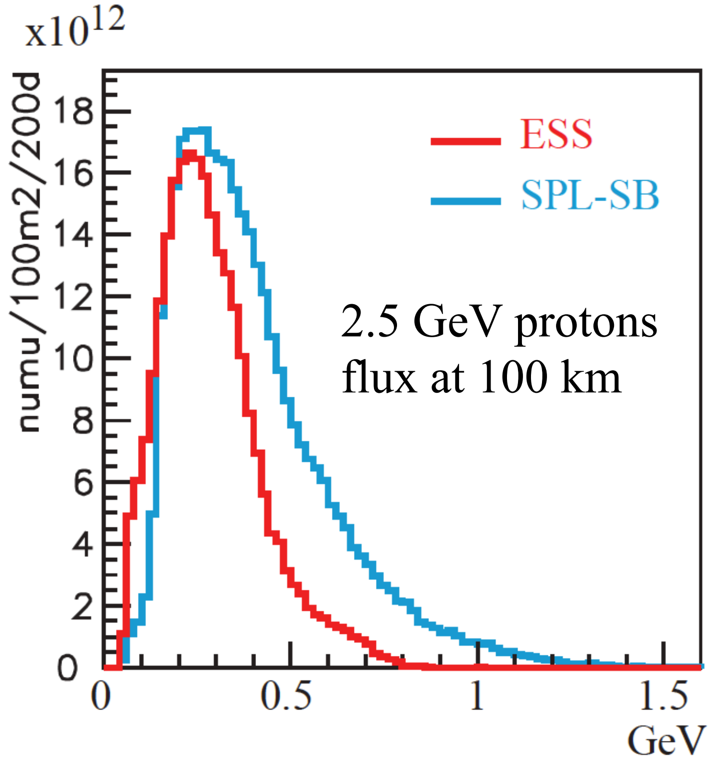


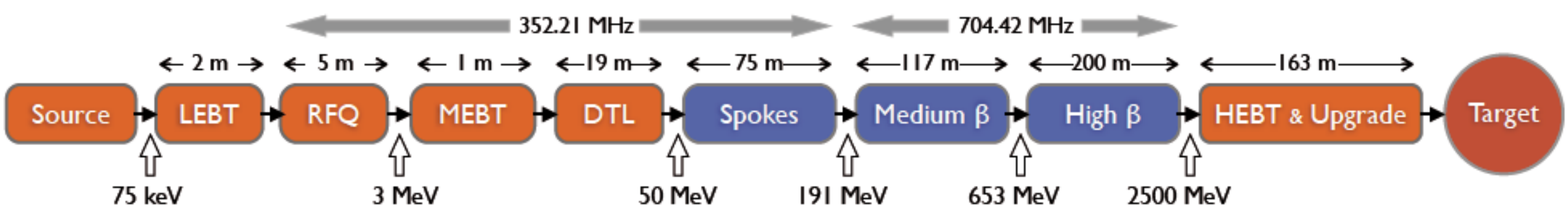
Requirements for adding a neutrino facility

- We must not affect the neutron program.
- Follow their schedule.
- Use as much as possible neutron facilities.
- For anything added, be synergetic when possible.
- Moderate cost.
- Kindly ask them to keep their choices compatible with neutrino needs (if this doesn't increase the neutron budget).

How to add a neutrino facility?

- with 2.5 GeV proton: ~300 MeV neutrinos
- Linac modifications: double the rate (14 Hz → 28 Hz)
  - one pulse for neutrinos and one pulse for neutrinos (5 MW each)
- additional RF power to drive the two beams (neutron production and neutrinos)
  - upgradable power sources
  - or double the power sources (free space has to be foreseen since now)

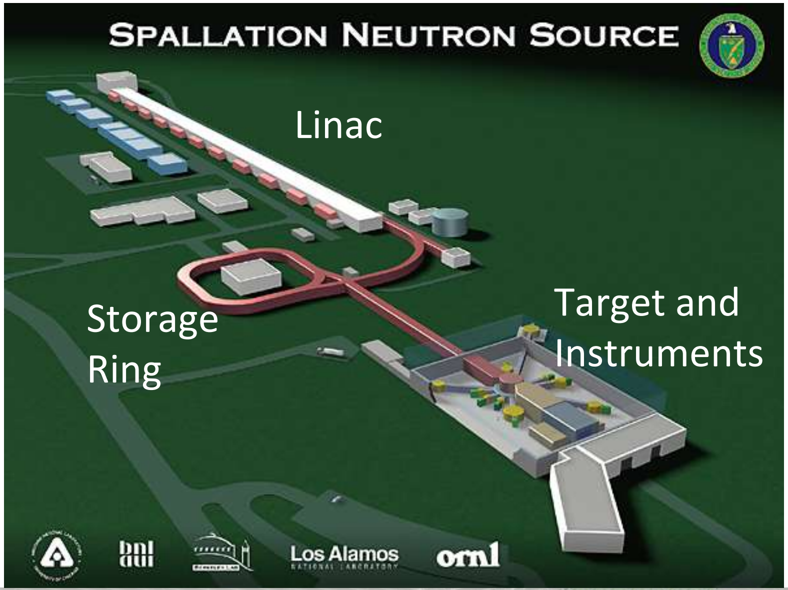


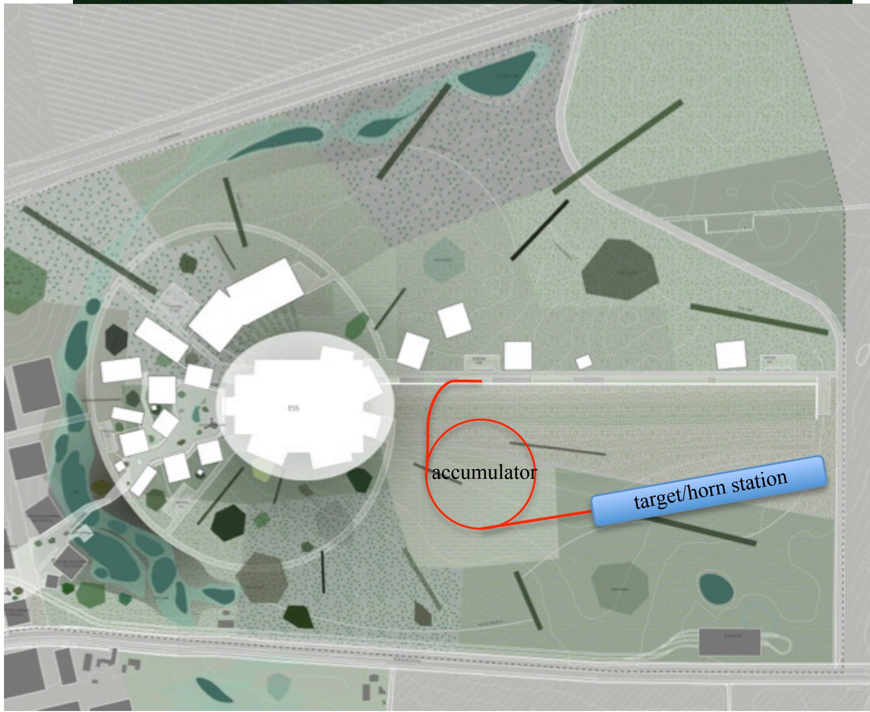


How to add a neutrino facility?

- **Accumulator** (ø 143 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA, power consumption, Joule effect)
  - H^- source (instead of protons)
  - space charge problems to be solved
- Neutron users have also expressed an interest for the accumulator (increase of neutron brightness).
- Other neutrino users using pions (from neutron target) decaying at rest need short pulses.
- Target station (studied in EUROnu)
- Underground detector (studied in LAGUNA)
- Linac and accumulator could be the first step towards the Neutrino Factory

(http://lanl.arxiv.org/abs/1212.5048)

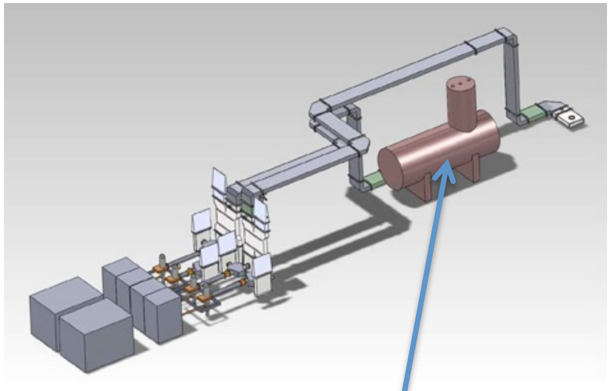




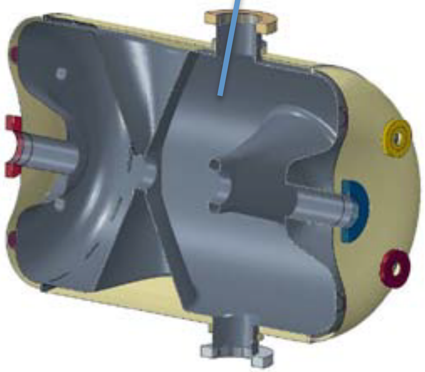

Existing expertise

Linac and RF power source tests

- A prototype 352 MHz spoke cavity for the ESS linac will be tested in the **FREIA Laboratory at Uppsala University** already as from July 2014 in a cryostat at 14 Hz pulse frequency and at the full instantaneous power required for ESS proton acceleration.
- As part of this neutrino project, the power supplied to the 352 MHz power source would be doubled and the pulse frequency raised to 28 Hz, thus doubling the average power to the cavity.
- The influence of this higher power on the operation of the cavity and on the capacity to cool the cavity itself and, in particular, its RF coupler will be studied.



Layout of the 352 MHz RF source, wave guides and test cryostat in the FREIA hall

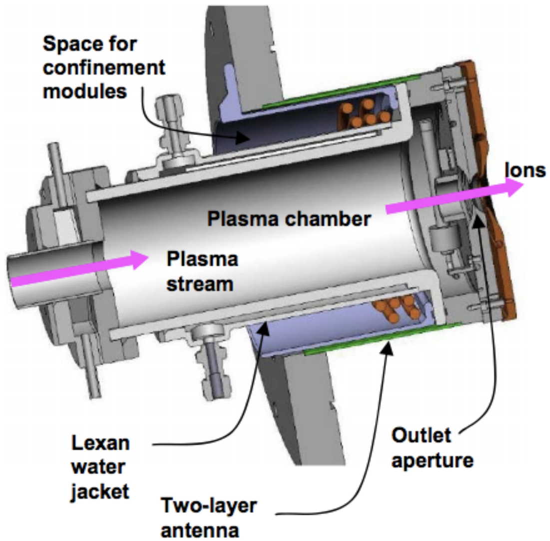


ESS Spoke 352 MHz Accelerating Cavity

Accumulator

- A problem with the enormous amount of protons stored at comparatively low energy in the accumulation ring is **the space charge which leads to a defocusing of the stored beam**.
- For a charge of 10^{15} protons stored for 2.86 ms in 450 m circumference storage ring, this defocusing effect is critical.
- A way to alleviate this problem is to divide the stored charge on **four accumulation rings**, thereby reducing the defocusing effect by a factor 4.
- **Neutron community very interested about this new device.**
- This trick is already used for the CERN PS Booster ring.

The 4 rings of the CERN PS Booster (1972)



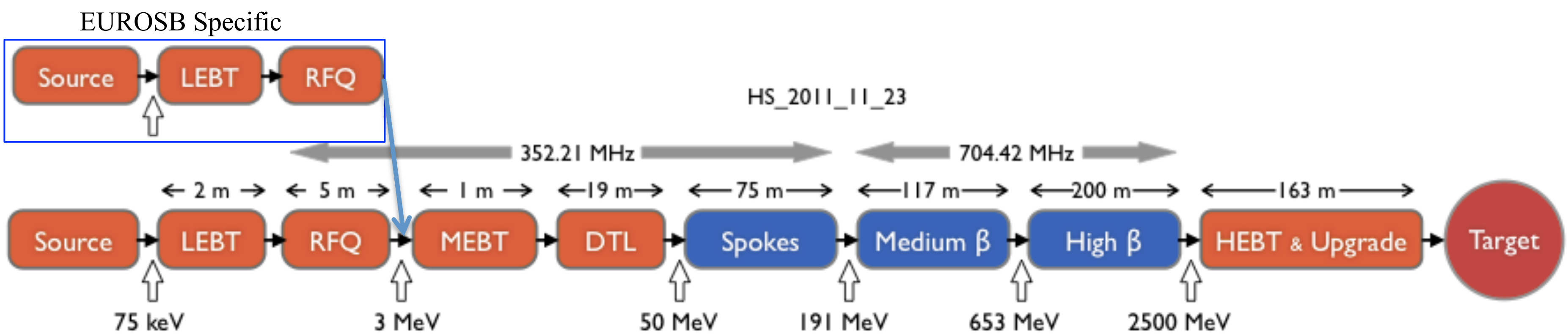
H^- Source

Parameter	Unit	ISIS	SNS	BNL	CERN, L4	ESS ν	SPL
Beam Energy	keV	16-35	65	35,40	45	75	45
Pulse duration	ms	0.5	1	0.8	0.4	3	1.2
Repetition Rate	Hz	50	60	6.6	1	14	50
H^- current	mA	35	60	65	80	62.5	80
H^- production mode		Cs-Arc	Cs-Surf.	Cs-Surf.	Cs-Surf.	Cs-Surf.	Cs-Surf.
Plasma Heating							
Emmittance In RFQ Norm RMS	mmmrad		0.25		0.25	0.20	
Cs-consumption	mg/day	100	0.4	12			
Operation MTBM	weeks	5	6	36	52		

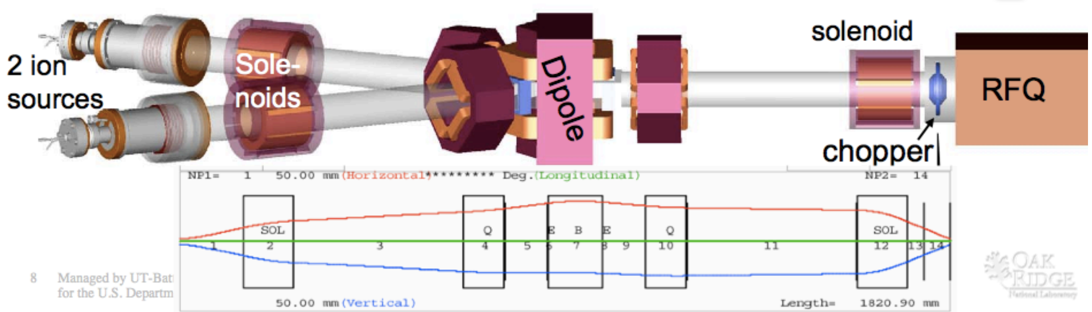
There exist sources that could give the required performance for EUROSB

Courtesy: J. Lettry

The LEBT



Or ?



At SNS:
two sources one RFQ !
Could we use the same RFQ for ESS and EUROSB ?
Constraints on RFQ phase?

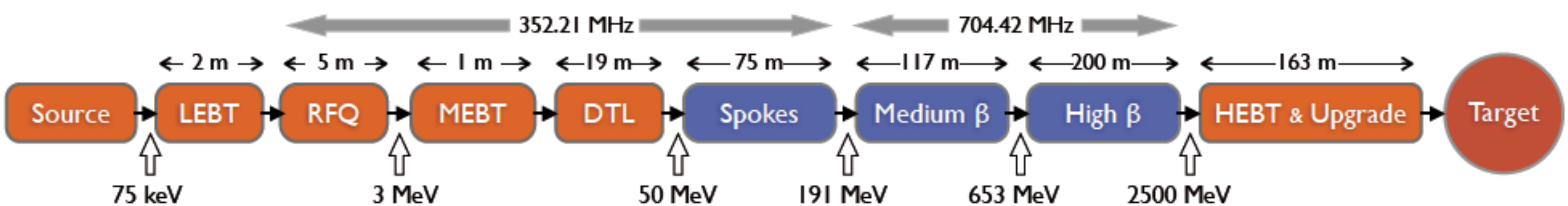
ESS: 0.2 mmmrad 4D norm Waterbag distribution at entrance RFQ

Source-LEBT

- The Source is feasible (cmp existing developments)
  - Estimate price by scaling from existing source developments
  - SNS source is close to EUROSB requirements
  - Get measurements from existing sources for simulations (SNS, CERN …)
- Simulations of LEBT including RFQ
  - Can the RFQ work for interleaved H- and H+ pulses (i.e. use of same RFQ)?
  - If so, simulation of separate RFQ and common RFQ
  - Must not influence neutron performance (Powered dipole only for H-)
  - Measurement of the Linac 4 source and of the SPL cavities, exploiting the tools developed in the context of the SLHC-PP project to take into account RF imperfections should be included in the simulations
- LEBT Chopper requirements
  - Chop unstable part of source pulse
  - Ion source rise/fall time 50 ms and RFQ 100 ns
  - Gives time for RFQ stabilization

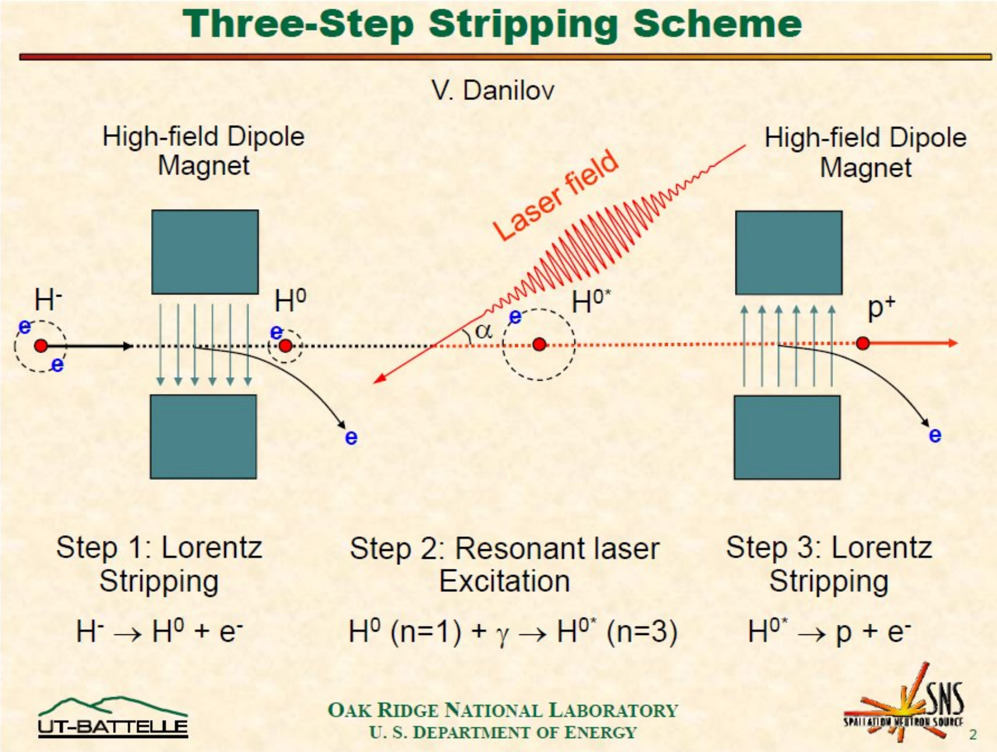
MEBT

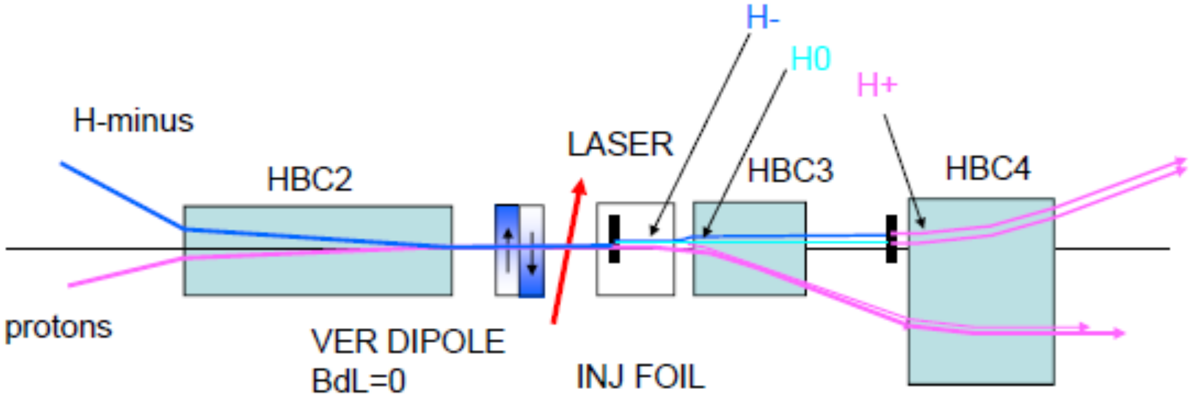
- Chopper in MEBT
  - Prepare structure of beam for later (ejection of beam from accumulator)
  - Advantageous to chop beam at lower energy
  - Fast: 2 ns rise-time for 352 MHz
- MEBT functions
  - Optics of MEBT may cause emittance growth
  - However useful for instrumentation, steering, optics tuning…
  - Collimation
  - Matching of RFQ and DTL in all three planes (10 quadrupoles and three 352.21 MHz buncher cavities)
  - MEBT contains a dump for tests i.e. for upgrade work



Stripping

- foil stripping not possible due to the high beam intensity
- Laser stripping necessary
- Promising tests at SNS

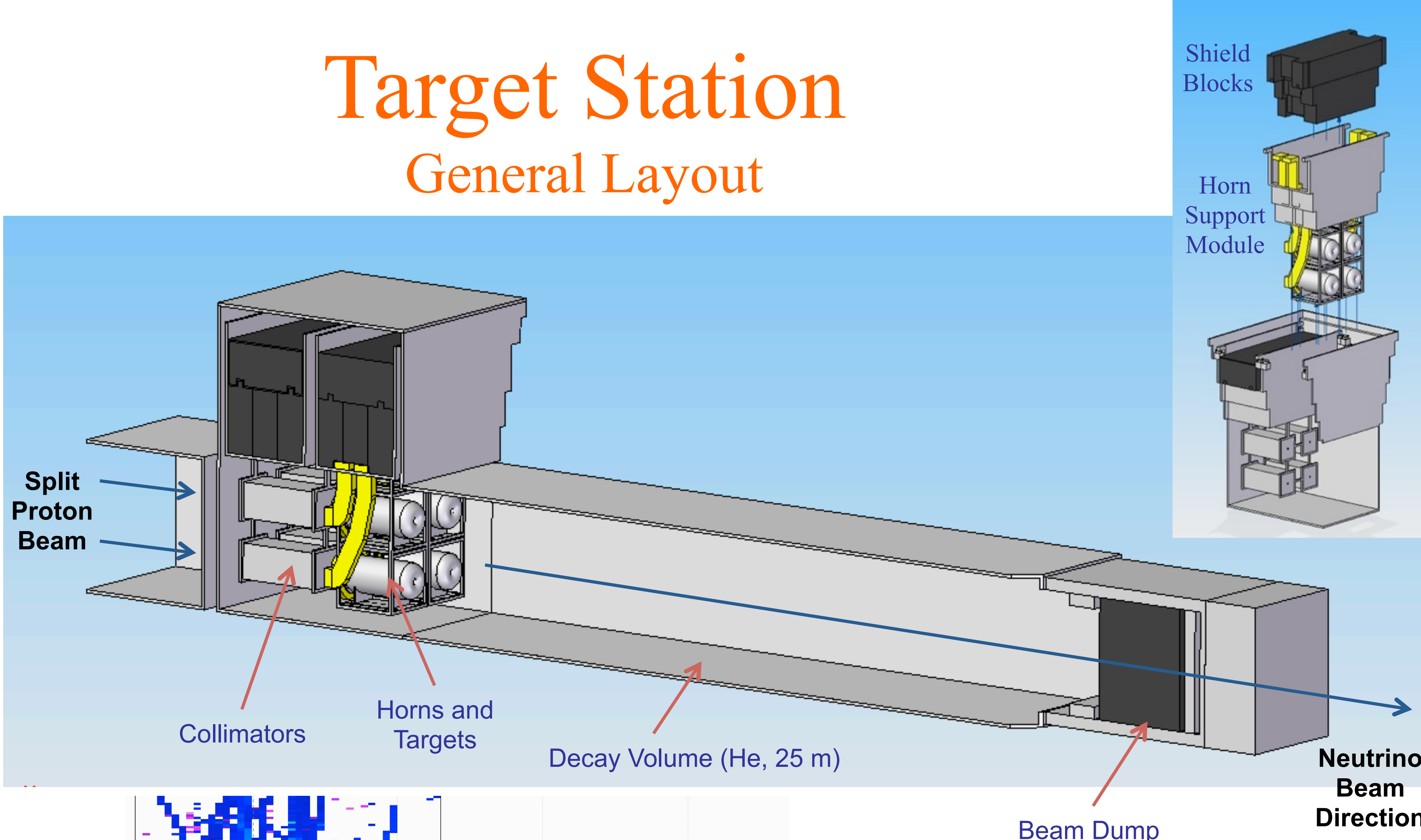


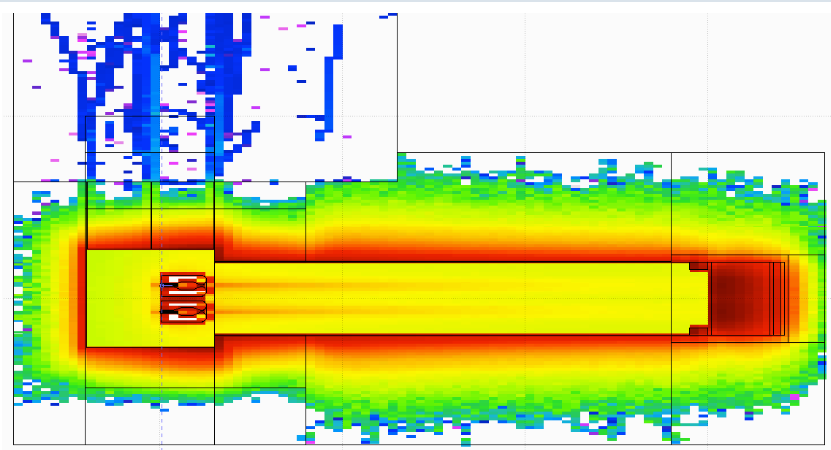


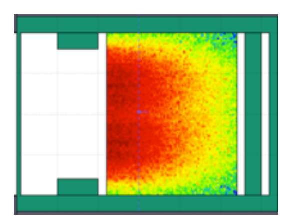
Insert:
•Vertical dipole with peak field ~3kG and BdL = 0 minimal effect on circulating beam and strip the outer electron from H-
•Laser crossing

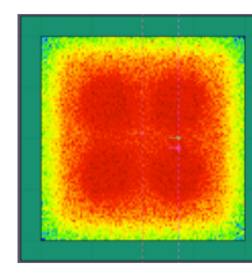
Target Station

General Layout

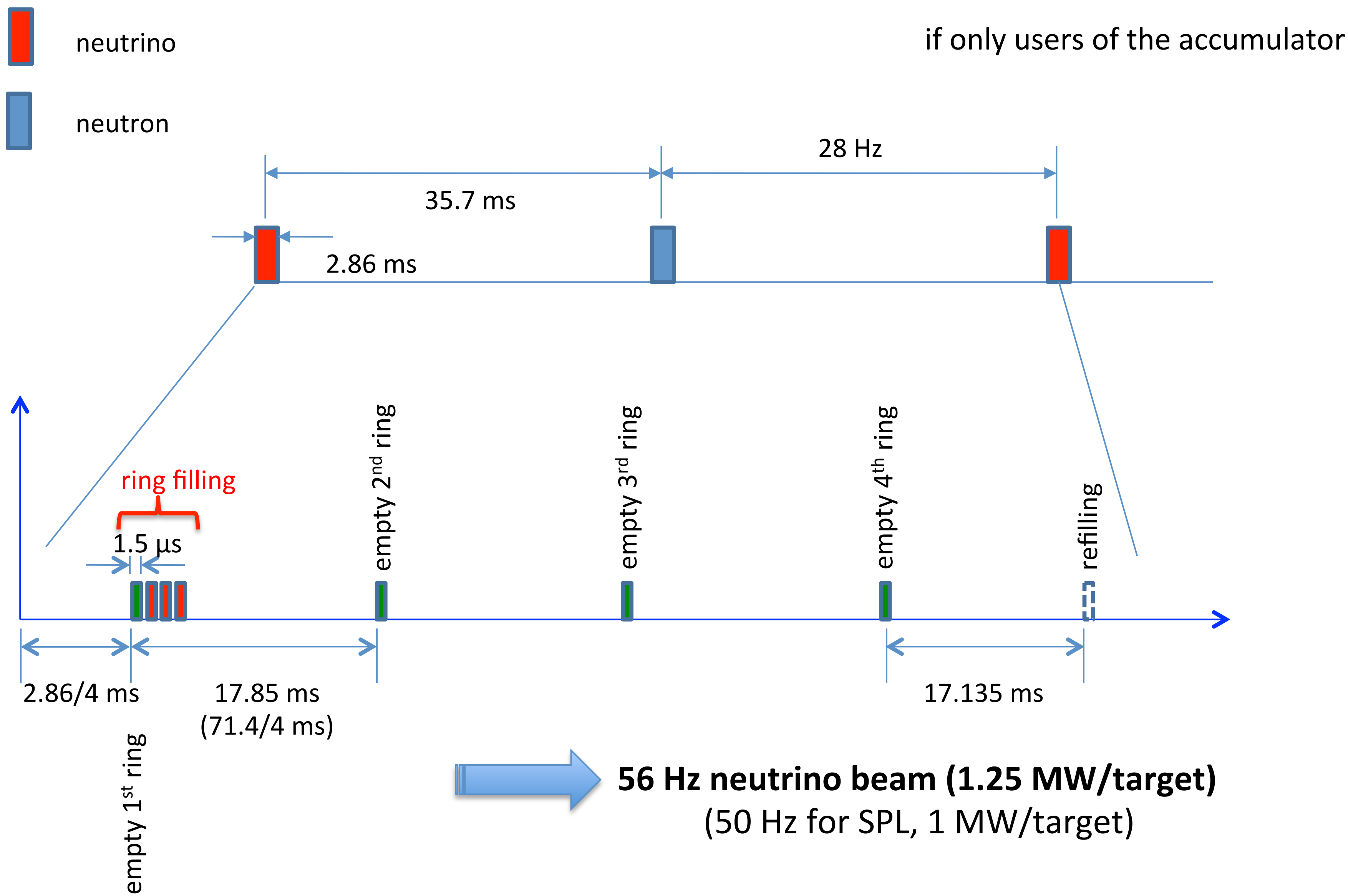








Possible Operation Timing



56 Hz neutrino beam (1.25 MW/target)
(50 Hz for SPL, 1 MW/target)

The MEMPHYS Detector (Water Cherenkov) (LAGUNA)

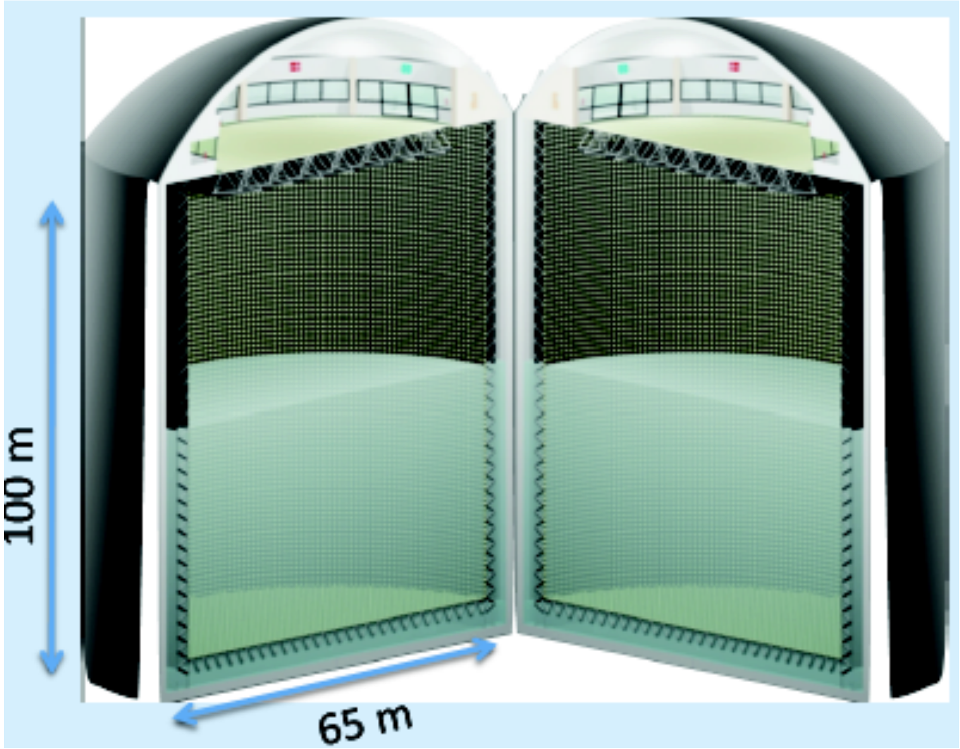
Mainly to study:

•Proton Decay (GUT)

- up to ~10^{35} years lifetime

•Neutrino properties and Astrophysics

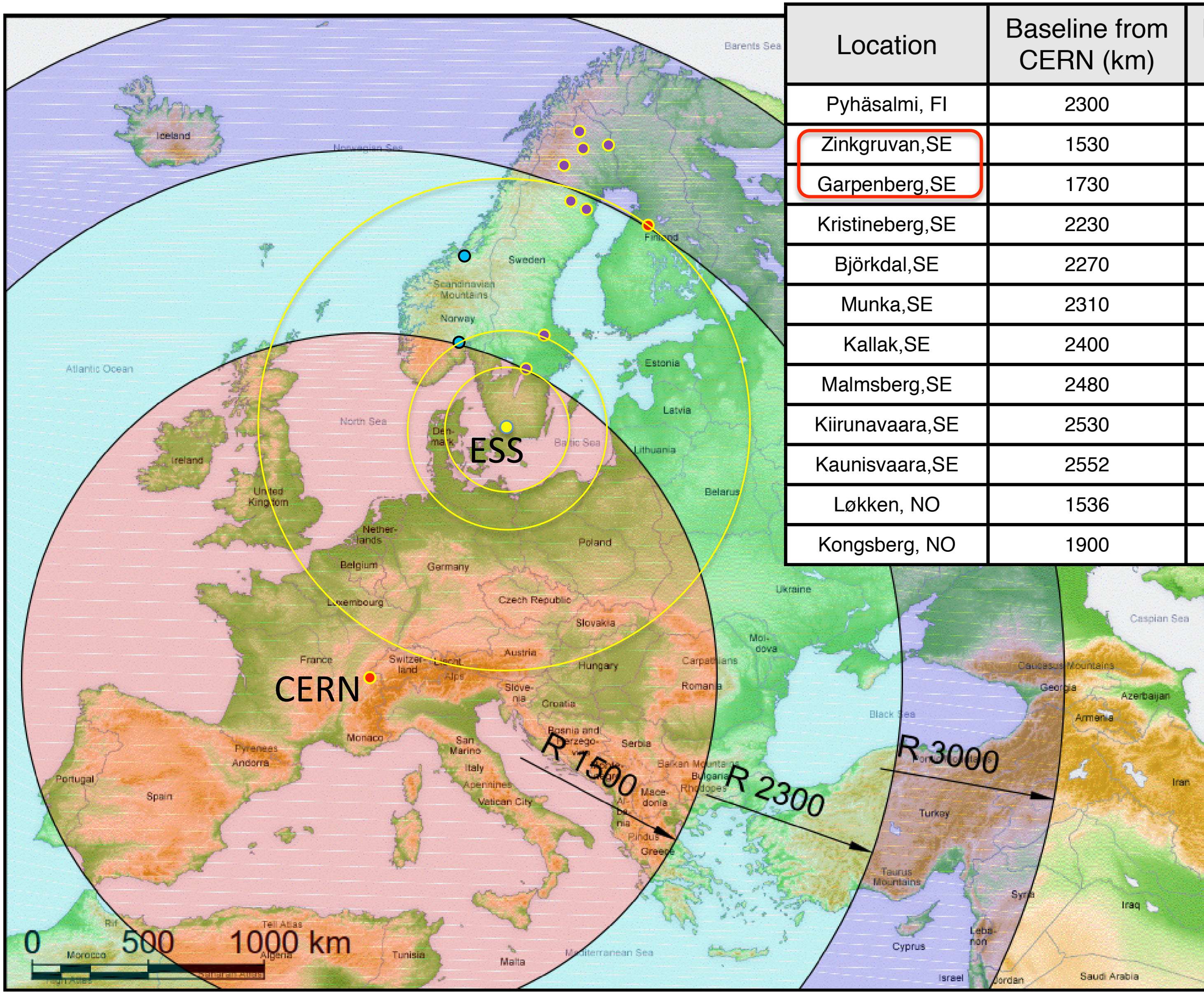
- Supernovae (burst + "relics")
- Solar neutrinos
- Atmospheric neutrinos
- Geoneutrinos
- neutrinos from accelerators (Super Beam, Beta Beam)



Water Cerenkov Detector with total fiducial mass: 500 kt:
- 2 Cylindrical modules 100x65 m
- Readout: 22.2k 8" PMTs, 30% geom. cover.

(arXiv: hep-ex/0607026)

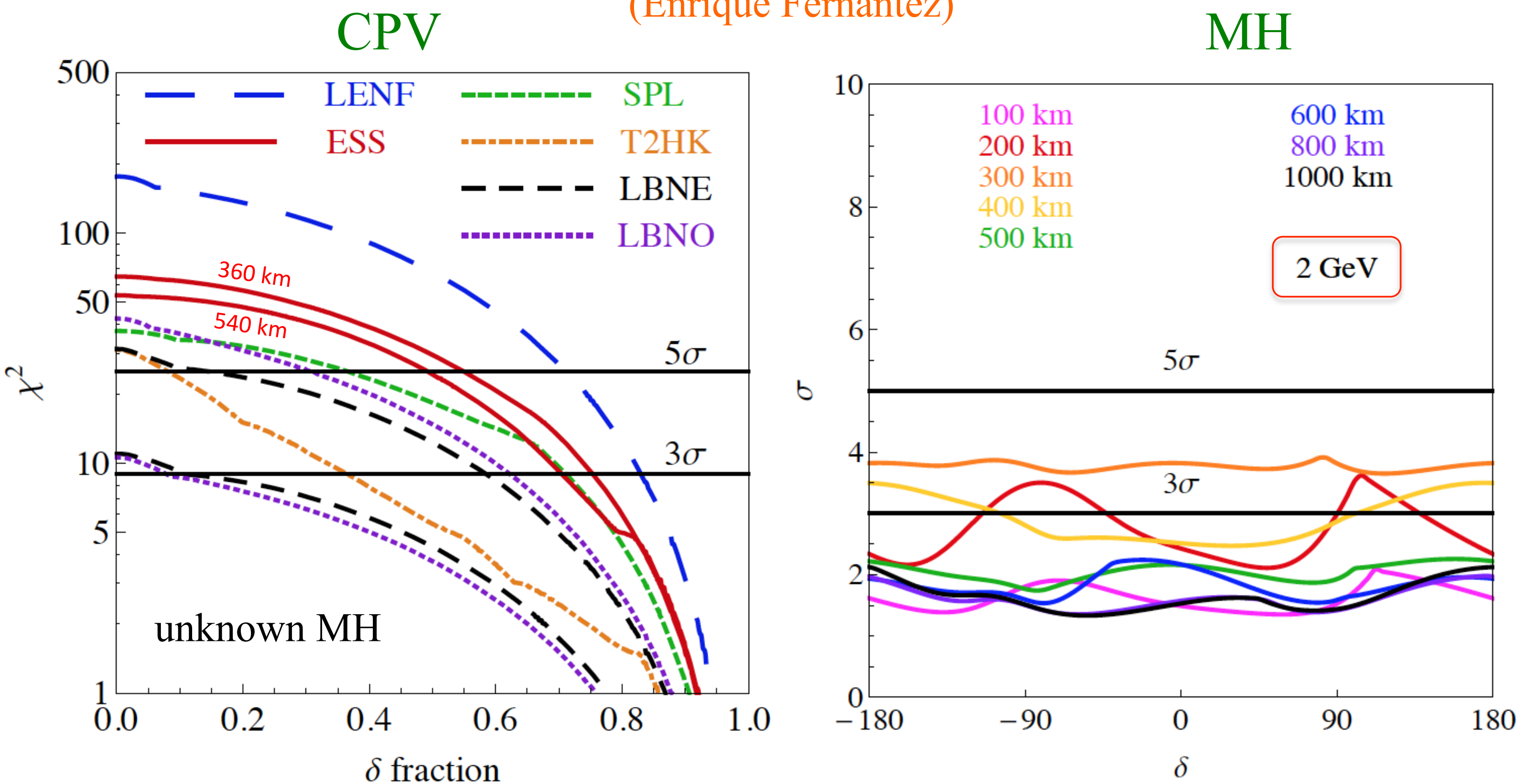
Detector location (LAGUNA)



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

Physics Performance for Future SB projects

(Enrique Fernantez)



- LBNE: 5+5 years, 0.7 MW, 10/35 kt LAr
- T2HK: 3+7 years, 0.75 MW, 500 kt WC (5%/10% syst. errors)
- SPL: 2+8 years, 4 MW, 500 kt WC (130 km, 5%/10% syst. errors)
- ESS: 2+8 years, 5 MW, 500 kt WC (2 GeV, 360/540 km, 5%/10% syst. errors)
- C2Py: 20/100 kt LAr, 0.8 MW, 2300 km

Conclusions

- ESS is under construction
  - very intense source of protons, 5 MW, 2-3 GeV
  - more than 10^{23} protons/year
  - well defined schedule
- Modifications are needed to transform ESS to neutrino facility
  - Double the rate
  - Add an accumulator
  - Add a target station
  - Underground detector (MEMPHYS), mines available

  (Double the rate, Add an accumulator, Add a target station:) could be the first step towards the Neutrino Factory
- Very promising physics performance using EUROnu optimizations:
  - CPV: coverage up to ~60%
  - MH: could reach 5 σ combining atmospheric neutrinos
- First ESS beam 2019, full power/energy by 2023.

Collaborators are welcome…

(just email tord.ekelof@physics.uu.se, marcos.dracos@in2p3.fr)

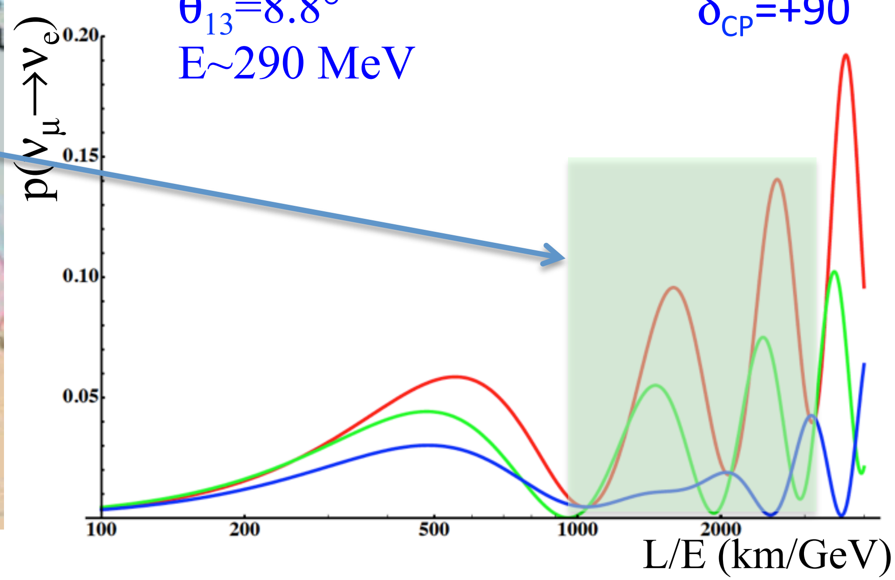
Backup

Possible Detector Locations

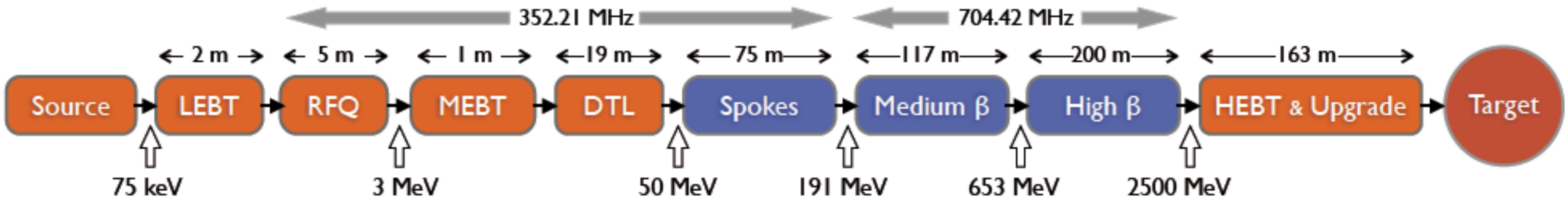
- Many mines (active or not) are available in Sweden
- What is the optimal position for CPV?
- How this project could help for MH?

Δm^2_{sun}=7.5x10^{-5} eV^2
Δm^2_{atm}=2.4x10^{-3} eV^2
θ_{23}=41.4°
θ_{12}=33.6°
θ_{13}=8.8°
E~290 MeV

δ_{CP}=-90
δ_{CP}=0
δ_{CP}=+90



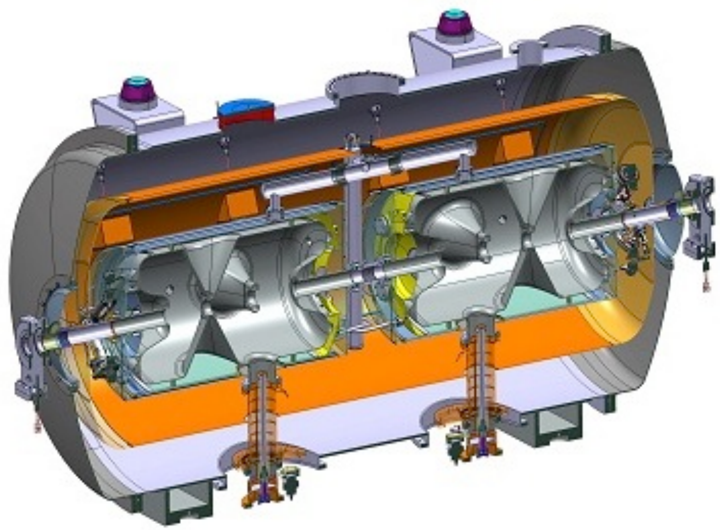
ESS proton linac

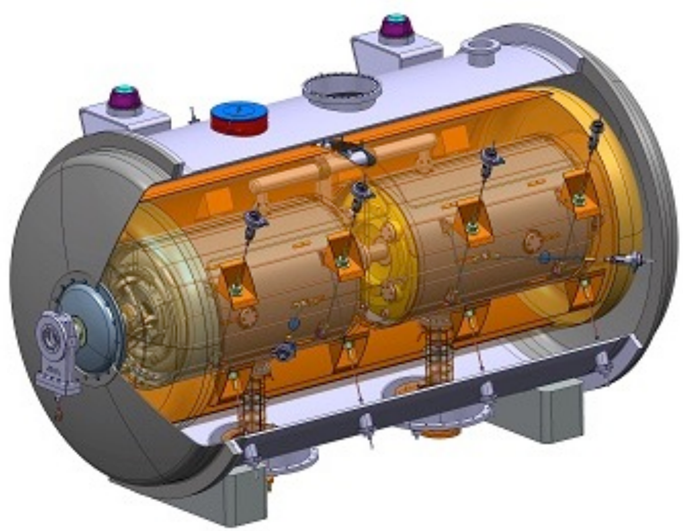


- Source: ion (H-) source, surface-plasma source (magnetron), semi-planatron, surface-plasma source with Penning discharge (Dudnikov-type source), RF volume source, etc. Multi-turn injection from a linac to an accumulator ring.
- LEBT: low energy beam transport, matching section between the ion source and the RFQ
- RFQ: pre-accelerator, Cockcroft-Walton or RFQ
- Chopper: to chop the beam so that it can properly fit into the RF bucket structure in an accumulator. This would greatly reduce the injection loss caused by RF capture.
- MEBT: Medium energy beam transport
- DTL: Drift tube linac. Low energy part (below 100 MeV, $\beta < 0.4$)
- Spokes: Spoked Resonator Cavity section
- Medium β: Medium energy part (100 MeV - 1 GeV, $0.4 < \beta < 0.9$)
- High β: High energy part (above 1 GeV, $\beta > 0.9$)
- HEBT: Medium energy beam transport
- Upgrade: spare space for future upgrades to go up to 3 GeV.

Spoke Cavities

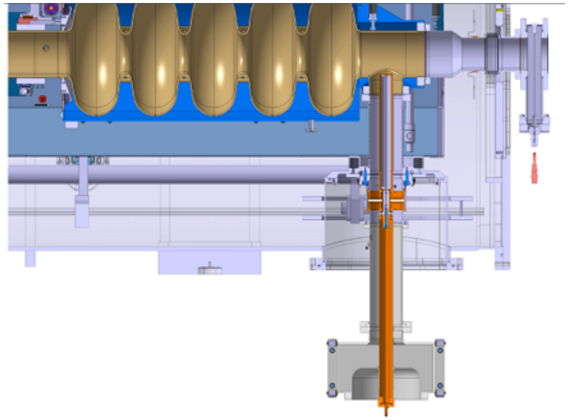
- ESS will transition to superconducting cavities at 88 MeV
- ESS will be the first accelerator to use 352 MHz double spoke cavity resonators
- Twenty-eight cavities with an accelerating gradient of 8 MV/m are required.
- Each cavity will operate at a nominal peak power of 320 kW
- What type of power source to choose?
  - Tetrode
  - Klystron
  - IOT
  - Solid State

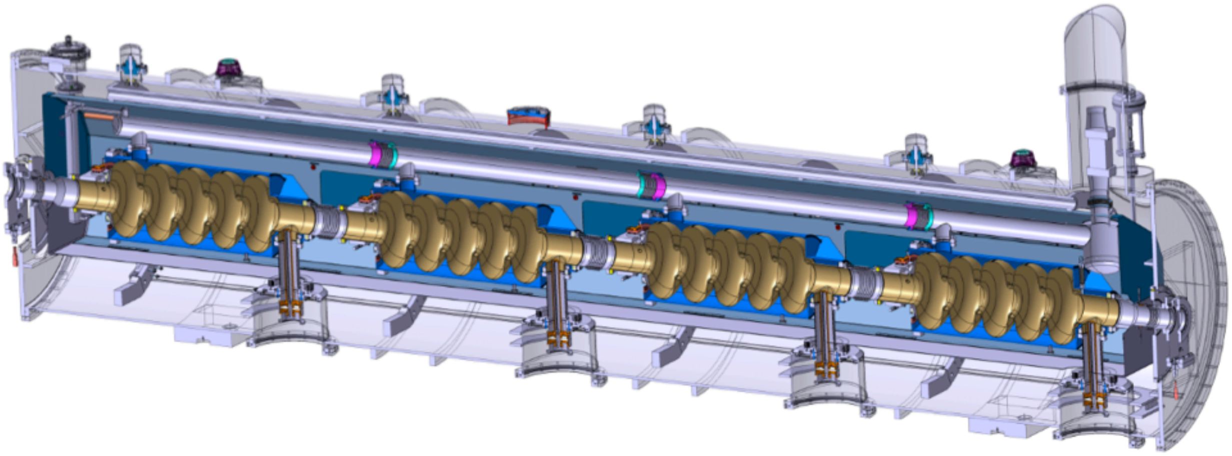




Elliptical Cavities

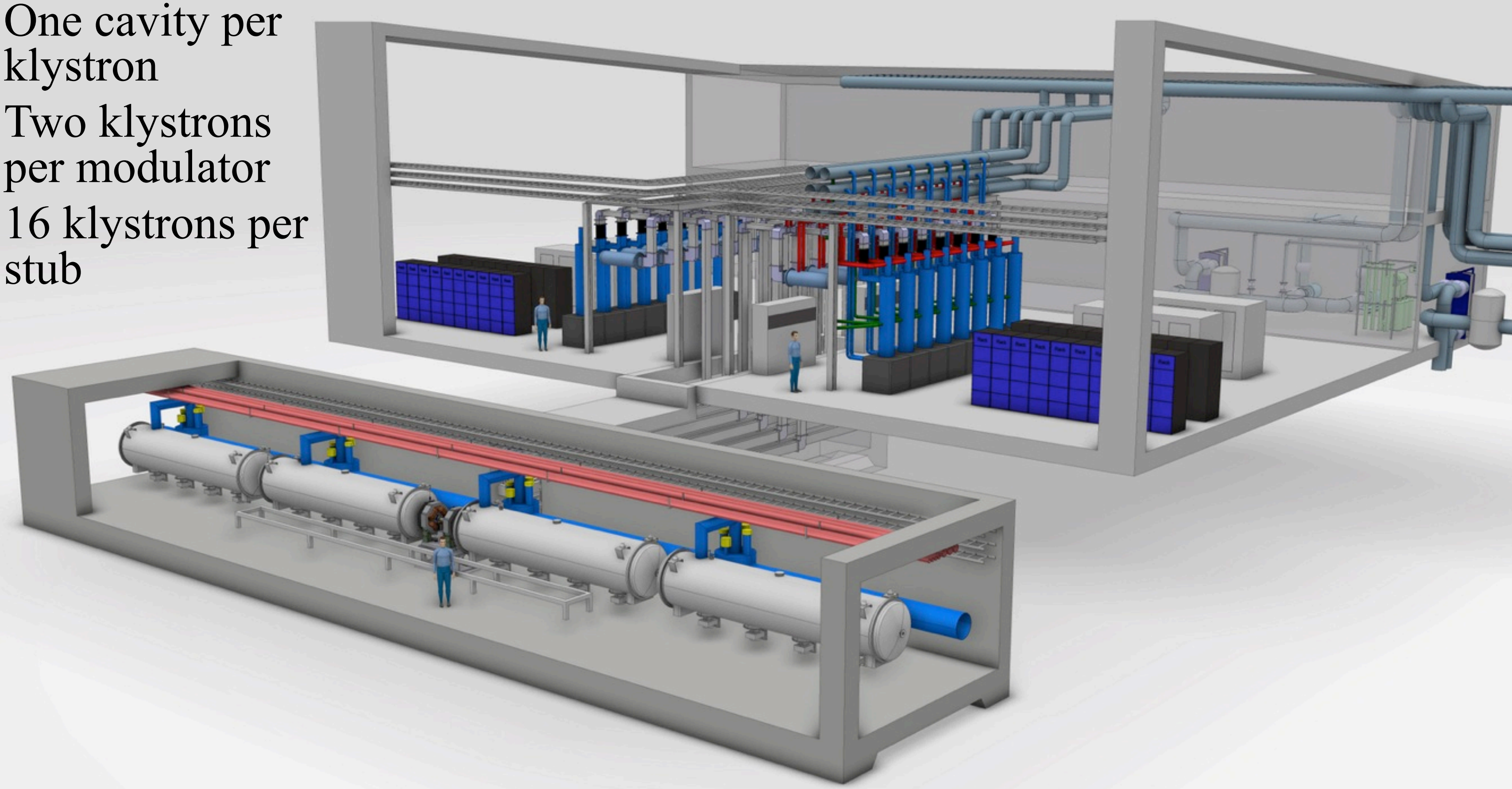
- Universal Cryomodule
  - Cryomodules are expensive and difficult to fabricate
  - Pick cavity β_g and number of cells
    - Optimize power transfer
    - Optimize length
  - Power in couplers is limited to 1200 MW (peak)
- Medium Beta $\beta_g = 0.67$
  - 6 cell cavities
  - Cavity length = 0.86 m
  - 32 cavities packaged in 8 cryomodules
  - Maximum peak RF power = 800kW
- High Beta $\beta_g = = 0.\ 86$
  - 5 cell cavities
  - Cavity length = 0.92 m
  - 88 cavities packaged in 22 cryomodules
  - Maximum peak RF power = 1100kW



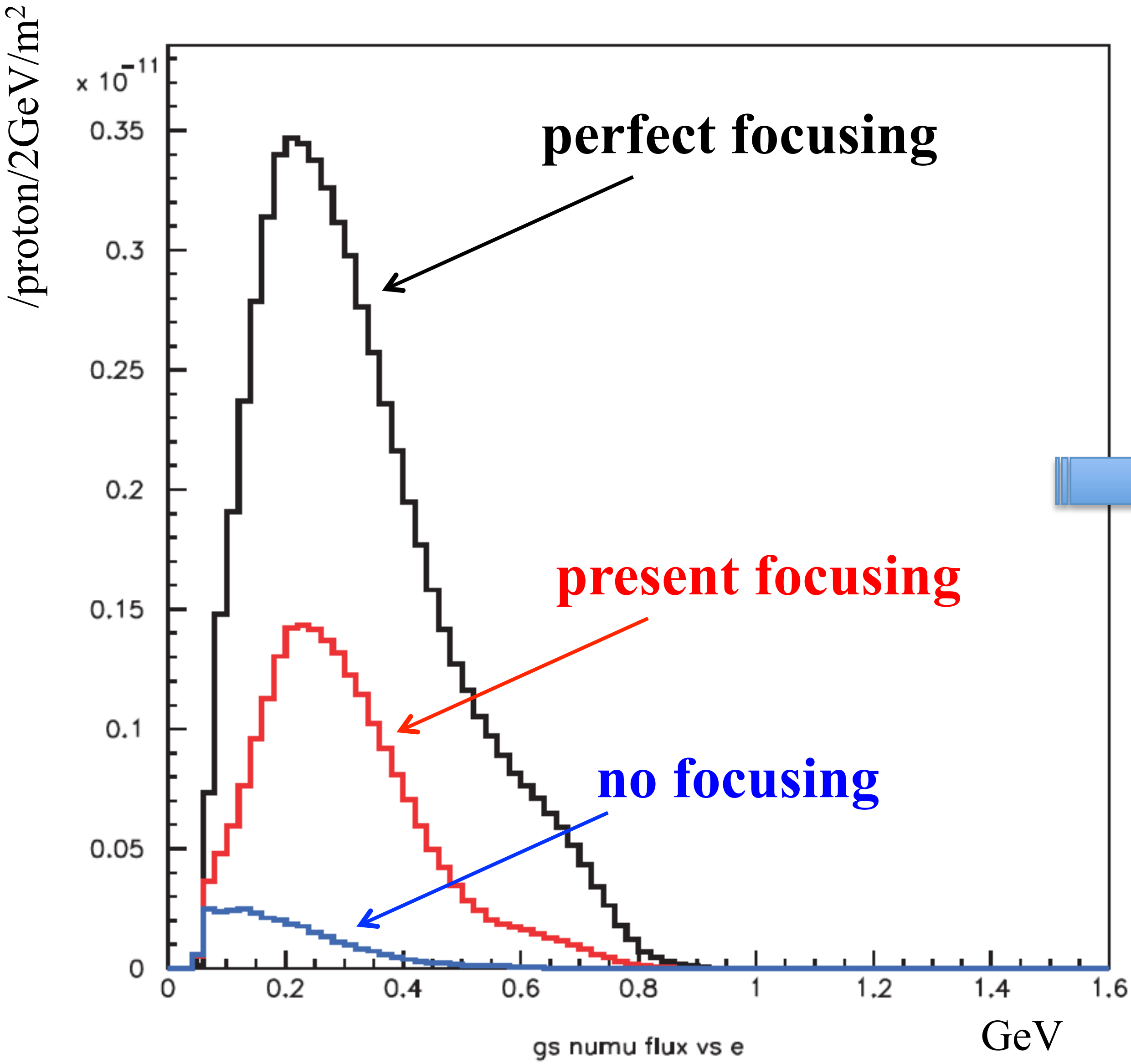


Elliptical RF System Layout

- One cavity per klystron
- Two klystrons per modulator
- 16 klystrons per stub



Horn Optimization



for 2.5 GeV

the horn is needed (x7.4 on the ν flux)