ESS Linac Modifications for ESSnuSB

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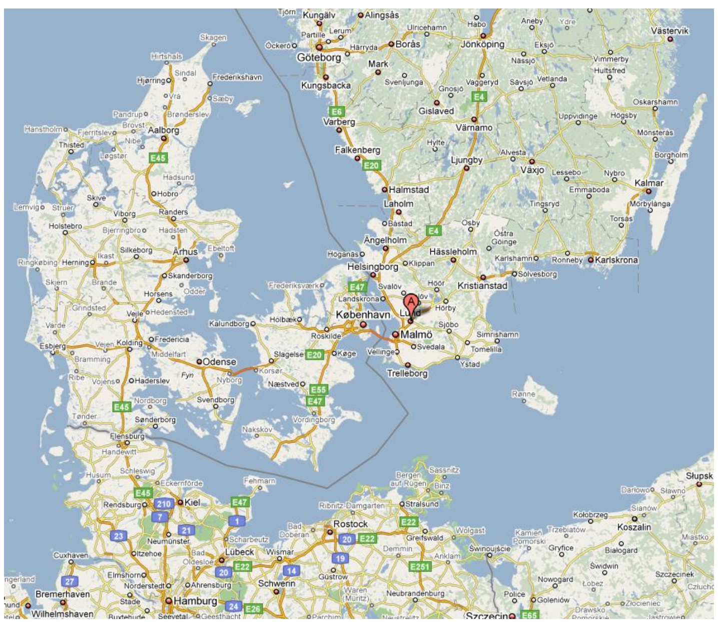
The European Spallation Source (ESS)

- ESS is a neutron spallation source that will be built by a collaboration of 17 European countries.
- ESS is located in southern Sweden adjacent to MAX-IV
  (A 4th generation light source)

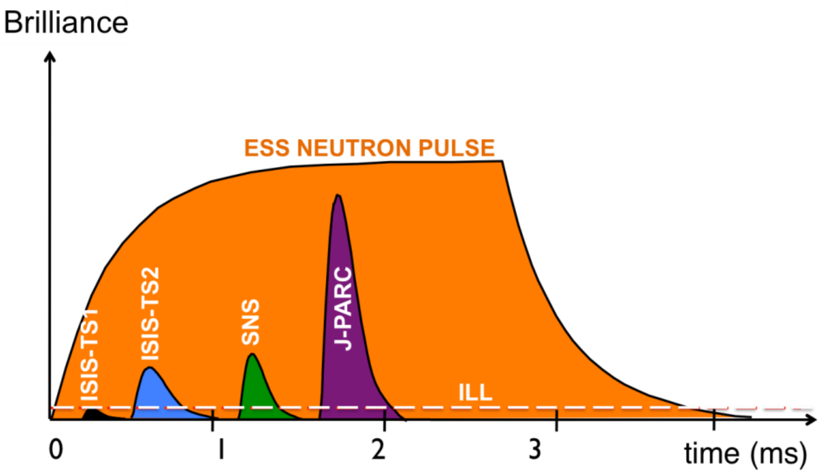


The ESS Linac

- The European Spallation Source (ESS) will house the most powerful proton linac ever built.
  - Average beam power of 5 MW.
  - Peak beam power of 125 MW
  - Acceleration to 2 GeV
  - Peak proton beam current of 62.5 mA
  - Pulse length of 2.86 ms at a rate of 14 Hz (4% duty factor)
- 97% of the acceleration is provided by superconducting cavities.
- The linac will require over 150 individual high power RF sources
  - with 80% of the RF power sources requiring over 1.1 MW of peak RF power
  - We expect to spend over 200 M€ on the RF system alone

The Long Pulse Concept

- Advantage - No compressor ring required
  - No space charge tune shift so peak beam current can be supplied at almost any energy
  - Relaxed constraints on beam emittance
    - This is especially true if the beam expansion system for the target is based on raster scanning of the beam on the target.
  - No H- and associated intra-beam stripping losses
  - Permits the implementation of target raster scanning
- Disadvantage - Experiment requirements “imprint” Linac pulse structure
  - Duty factor is large for a copper linac
  - Duty factor is small for a superconducting linac



Requirements for ESSnuSB

- 5 MW for neutrons
  - Long pulse does not need a compressor ring
  - Can use H- or H+
- 5 MW for neutrinos
  - Needs a compressor ring
  - Requires H-
- Peak power in SRF elliptical couplers not exceed 1.2 MW

Increased Duty Factor

- Maximum peak power in RF couplers in ESS baseline design is 1.1MW
- Solution:
  - Additional power provided by increasing r.m.s beam current while keeping peak beam current constant by adding an additional beam pulse 2.86 mS in length
    - i.e increase the beam duty factor by a factor of two from 4% to 8%
  - ESSnuSB might want to package the additional 2.86mS beam pulse in multiple pulses

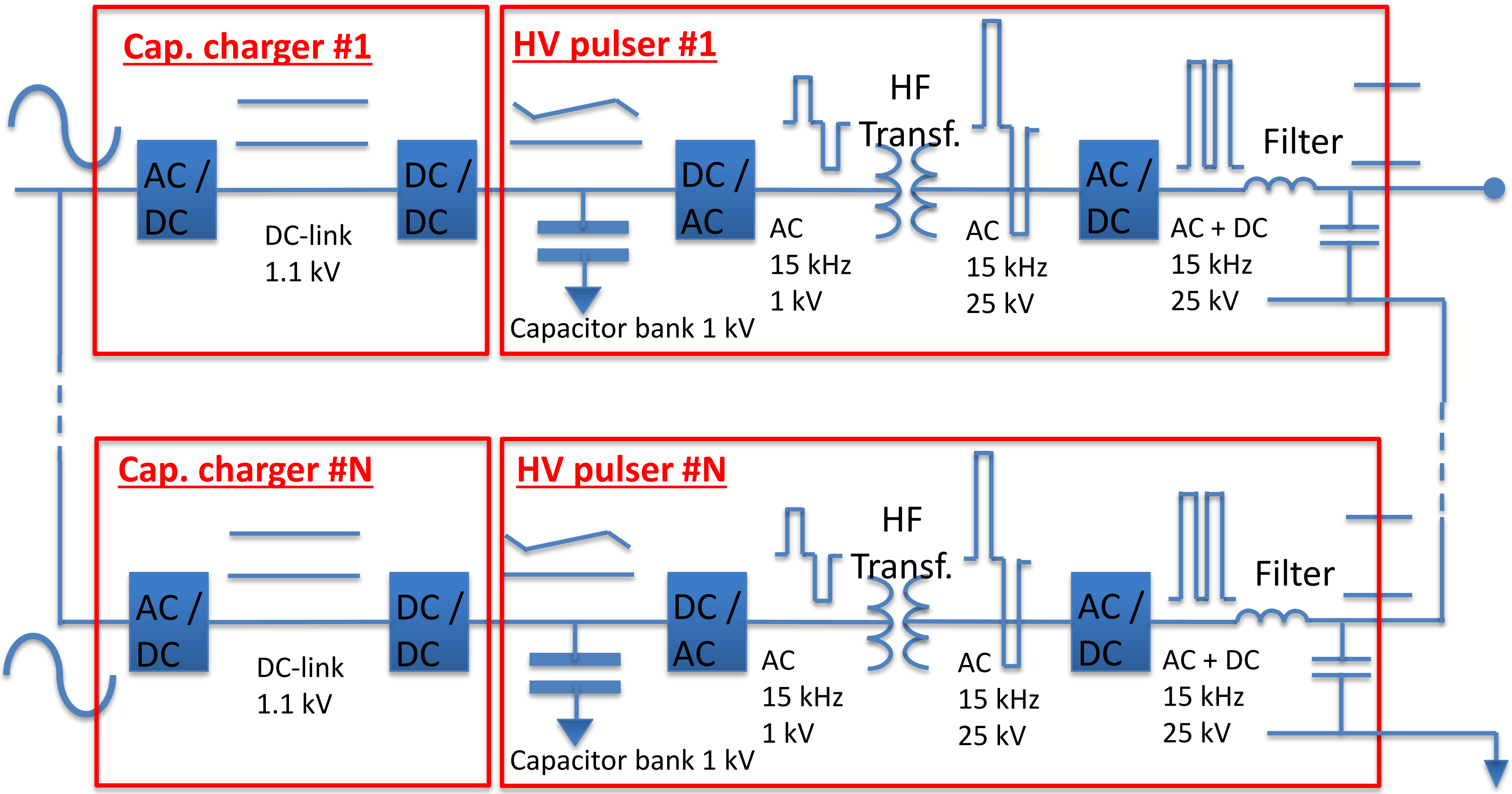
RF Power

- The majority of the power supplied to the Linac goes to the RF sources
  - 13 MW to RF sources
  - 7 MW for cryoplant, racks, power supplies, water skids, etc.
- RF Power budget
  - Power Amp (Klystron) efficiency = 60%
  - RF Overhead = 1.3
  - Modulator efficiency = 92%
  - Cavity efficiency = 98%
  - Total efficiency = 41.5%
- Timeline
  - Pulse length = 2.86 mS
  - Cavity fill time 0.2 mS (loaded Q = 7e5)
  - Modulator rise time = 0.1 mS
  - Timeline efficiency = 90.5%
- Total efficiency = 37.6%
  - 5MW of beam power requires 13.3 MW of wall plug power

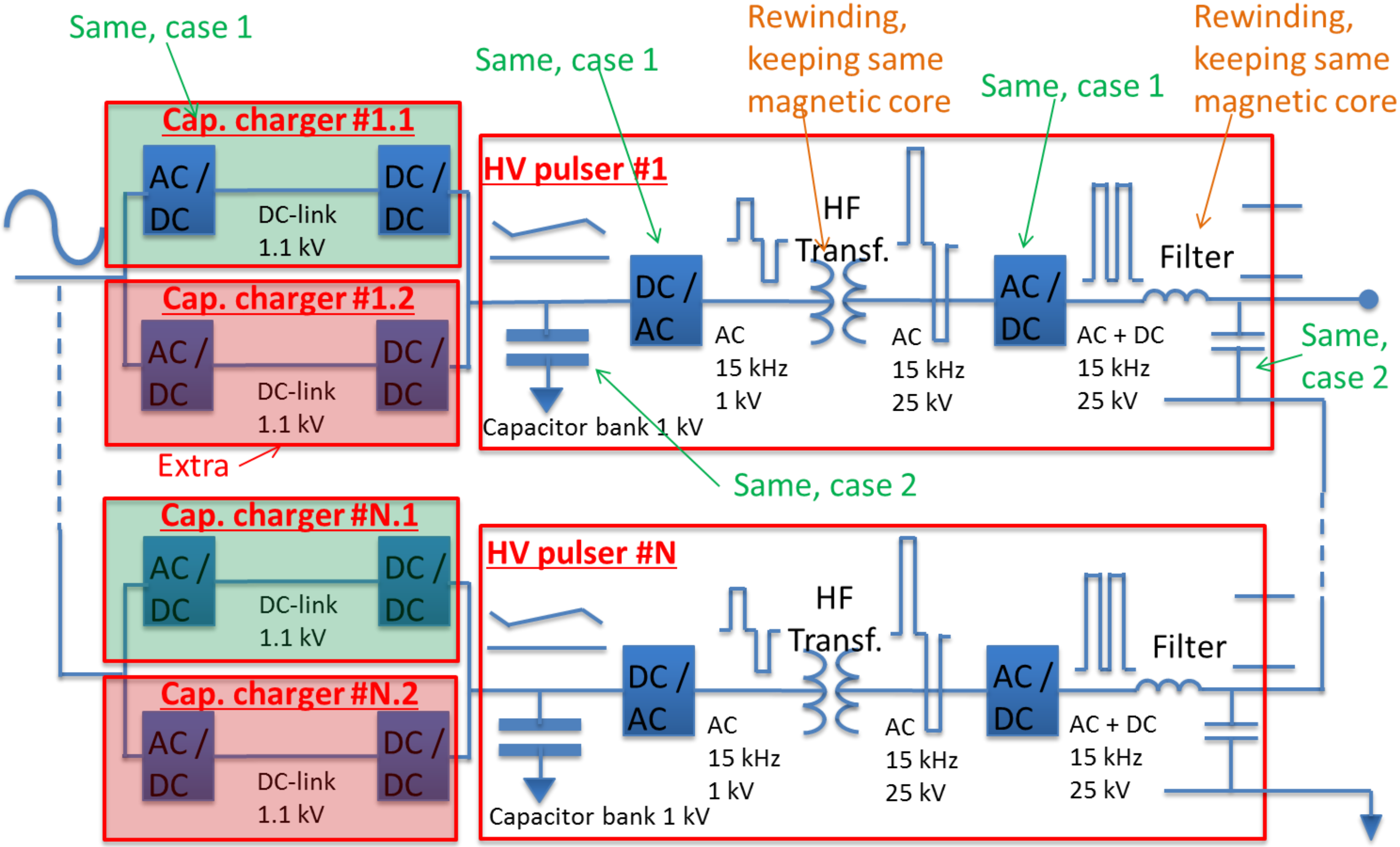
ESSnuSB Timeline efficiency

- 1 ESSnuSB pulse: timeline efficiency =90.5%
  - Extra power required = 13.3 MW
- 4 ESSnuSB pulse: timeline efficiency =79.2%
  - Extra power required = 17 MW
- 8 ESSnuSB pulse: timeline efficiency =68%
  - Extra power required = 22 MW

Klystron modulators for 14Hz operation (present most likely scenario = Stacked MultiLevel topology) (C. Martins)



Klystron modulators for 28Hz operation (C. Martins)



Same, case 1 = no modifications, impact on the lifetime due to thermal cycling (8 years instead of 25 years);

Same, case 2 = no modifications, same lifetime (25 years);

Impact on modulators when upgrading from 14 to 28Hz (C. Martins)

Cost Impact	**Per modulator**	**Total (45 modulators)**
1)- Adding extra capacitor charger modules	+ 60 kEURO	+ 3 MEURO
2)- Re-winding HVHF transformers and output filter inductors	+ 100 kEURO	+ 4.5 MEURO
3)- Labour costs (contract follow-up, testing, etc.)		+ 5 MEURO
Total cost increase for modulators' upgrade		**+ 12.5 MEURO (+ 30%)**

Footprint Impact	**Per modulator**	
Footprint required for additional capacitor chargers	~ 1.2m x 1m	

Impact on the AC distribution grid when upgrading from 14 to 28Hz (C. Martins)

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Cost Impact		**Total (45 modulators)**
1)- Add additional 10kV/600V distribution transformers (doubling the total quantity, keeping existent ones)		+ 2 MEURO
2)- Add additional LV power cables and switchboards (doubling the total quantity, keeping existent ones)		+ 1.5 MEURO
3)- Labour costs (contract follow-up, testing, etc.)		+ 2 MEURO
Total cost increase for AC grid upgrade *(only for LV grid; new buildings and CF expenses not included)*		**+ 5.5 MEURO (+ 100%)**

Other impacts (to CF)		
New buildings will be required for extra LV transformers and swichboards; Double footprint required.		
An additional HV 120kV/10kV power transformer will be required		
All HV distribution lines and protection devices at 120kV and 10kV levels will be doubled		

Cryogenics Safety Factors

The ESS cryogenics system will use the following formula for determining a cryoplant's cooling capacity at a given temperature:

$$C = F_o(F_{ud}Q_d + F_{us}Q_s) \qquad (7)$$

Where:
C = Total cooling capacity of cryoplant at a given temperature;
F_o = Operational safety factor;
F_{ud} = Uncertainty factor on dynamic heat loads (i.e. those associated with RF cavities & power couplers);
F_{us} = Uncertainty factor on static heat loads;
Q_d = Predicted dynamic heat load without any safety factor;
Q_s= Predicted static heat load with out any safety factor;

Heat loads

With contigency and distribution safety factor of 1.3

Table 1, Heat load estimation of CM, W

	2 K							5 K		50 K
	Static				Dynamic			Static	Dynamic	Static
	Others	Valves	Coupler	Total	Beam	Cavity	Total	g/s	g/s	
Spoke CM	3.3	0.2	3.5	**7.0**	1.5	5.0	**6.5**	0.092	0.000	**30.0**
Medium beta CM	6.3	0.2	6.8	**13.3**	3.3	20.0	**23.3**	0.092	0.000	**46.5**
High beta CM	6.3	0.2	6.8	**13.3**	3.3	24.4	**27.7**	0.092	0.000	**46.5**
CMs in Total	676				1263			5.2	0.0	2436

Table 3, heat load estimation of Linac cryoplant, W (on base of Table 2)

	2 K		5 K		50 K		
	Static	Dynamic	Static g/s	Dynamic g/s	Static		
Predicted CM in Total	676	921	5.2	0.0	2436		
Installed CM in Total	**1166**	**1060**	**9.0**	**0.0**	**3642**		
Predicted CDS supply	142				147		
Predicted CDS return	409				4654		
Predicted CDS in Total	551				4801		
Installed CDS in Total	**824**				**7177**		
Installed in total	**3050**		**9.0**		**10819**		
4,5 K Equ. W	9150		905		773		
4,5 K Equ. Total	10827					238	2.575982
Electrical power, MW	2.56						

Table 2, CM Safety factor

	F0	Fud	Fus
2 K	1.15	1	1.5
5 K	1.15	1	1.5
50 K	1.15		1.3

Table 4, Distribtution safety factor

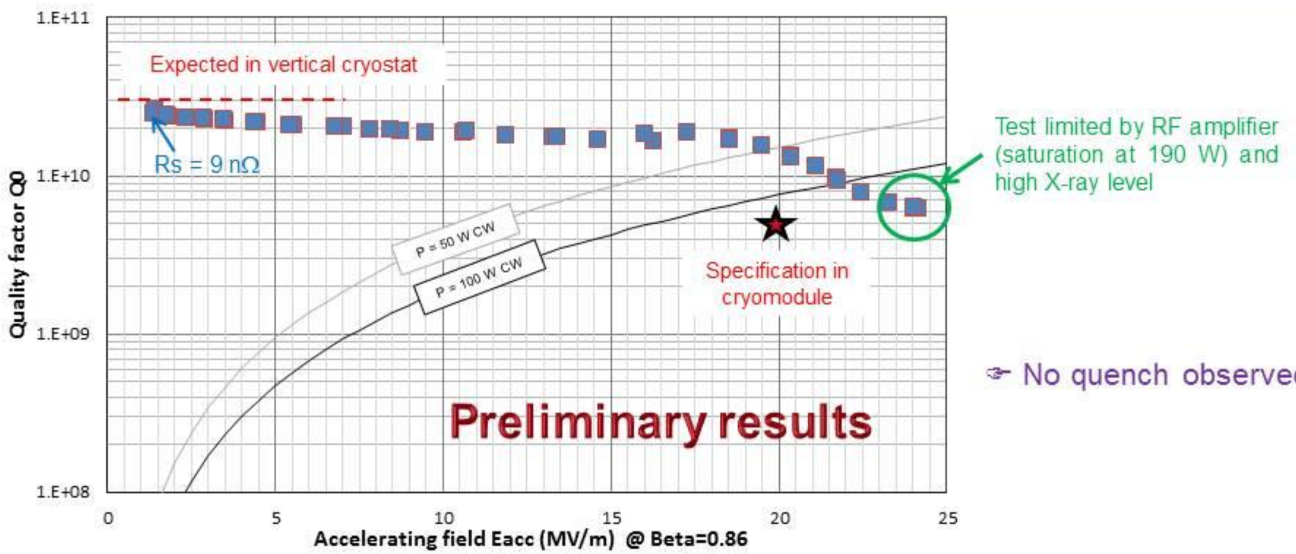
	F0	Fud	Fus
2 K	1.15		1.3
50 K	1.15		1.3

- Very likely the same cryogenic distribution system can be used to remove the expected higher heat load from the cavities.
- The cryogenic plant will most likely need to be upgraded to cover the needs of ESSnuSB.

First cold test result of first ESS high beta prototype cavity

FIRST COLD TEST RESULT OF FIRST ESS HIGH BETA PROTOTYPE CAVITY

- Measurements done the 22th of May 2014 in vertical cryostat at CEA Saclay
- Testing conditions: CW mode
- Operating temperature: 2 K
- Resonant frequency of π mode (measured): 704.292788 MHz
- External coupling (measured) : Q_i = 6.5e9 ± 1e9, Q_t = 6.8e12
- Parameters used : G = 241, R/Q = 435.35 Ω (at β = 0.86), L_{acc} = 0.92 m



☞ No quench observed

Next plans:

- Measurement of resonant frequency of 1st bandpass mode at 2K
- Measurement of resonant frequency of HOM at 2K
- If possible, increase accelerating field up to the quench limit
- Perform heat treatment at CERN at 650°C under vacuum

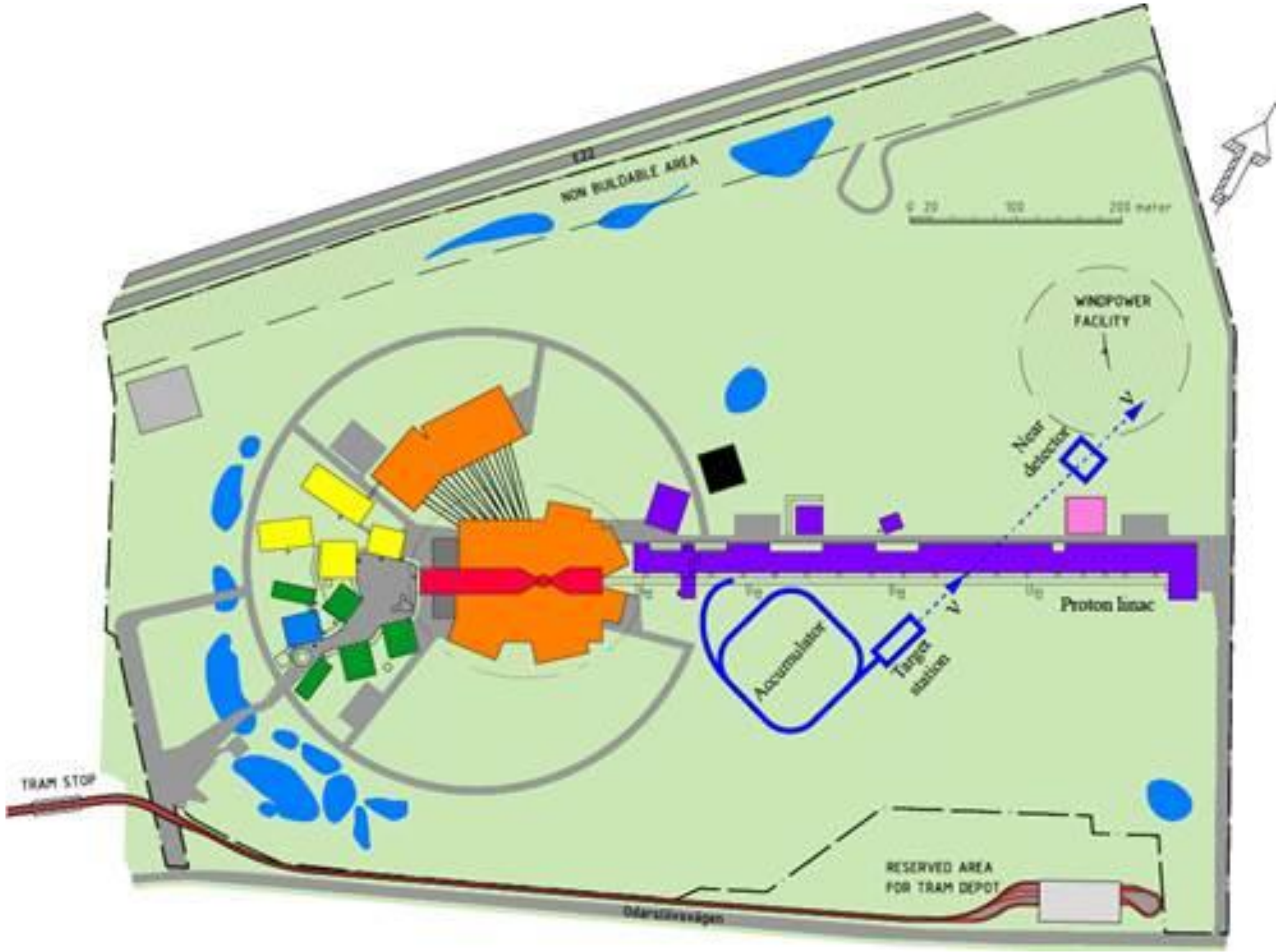
Major Issues

- Modulator Charging
- RF Gallery Transformers
- Site Power distribution
- Klystron Collector Cooling
- Circulator cooling
- RF Coupler cooling
- Front-End Water skids
- Cryo loads
  - Dynamic loading
  - Extra Beam loss
- H- and H+ acceleration

Site Layout

- Assuming the nominal accelerating gradient one could add 15 cryomodules of 66 MeV, so the final energy could be increased up to 3 GeV.
- Very little space is foreseen for reception of equipment, equipment tests, storage of equipment/spares.
- The extraction point can be at the end of the contingency space in the linac.
  - Limiting H- stripping losses to 0.1 W per meter
  - Assuming that the beam extraction line towards the accumulator can be filled to 75% with dipoles
- The beam extraction line should branch off from the main linac with a radius of
  - 70 m for a 2 GeV, 5 MW beam
  - 133 m for a 3 GeV, 5 MW beam
- The neutrino beam (and its preceding beam dump and target) will be in a line that crosses the linac tunnel.
  - The neutrino decay line will most likely have to be below the linac level,
  - The neutrino target will have to be located sufficiently deep
  - potential irradiation risk for ground water

Cartoon of ESSnuSB Site Layout



Utilities

- The main power station is designed with enough redundancy (2 main transformers) to enable
  - continued operation of ESS in case of failure of HV equipment
  - which has long (2 years) procurement time.
  - The main cost of the main power station is linked to the switch gear and not to the actual transformers (only around 20%).
- A bay for a third transformer is foreseen to potentially provide power to the neighboring science village.
  - The presently empty bay can either be used for the science village or for an upgrade of ESS.
- The trenches for the HV power cable are compatible with the needs for a ESSnuSB upgrade without major modification.
- Although the sizing of the cooling pipes has been defined,
  - However the margins within the present pipe sizes are not yet precisely known.
  - The main water distribution pipes between the utility building and the klystron gallery, cryogenic plant will need to handle twice the flow.
- Additional outside space is needed to:
  - add electrical transformer buildings to supply the klystron modulators.
  - upgrade the HVAC.
  - increase the size of the utility building in order to house more heat exchangers and pumps

Front-End

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- Trim magnets are included in quadrupoles, and they may be difficult to pulse.
  - Not being able to pulse the trim magnets may inhibit simultaneous operation of protons and H-
- The cooling capacity in all normal conducting cavities needs to be upgraded.
- The option to merge beams before the RFQ should be assessed.
  - The merging would be done in the area of the space charge compensation which seems very difficult.
- The option of adding a complete H- front-end with source, RFQ, MEBT should be considered.
  - There seems enough space to fit racks for a 2nd complete front end.
  - The ion source can be pushed back by up to 3 m.
  - This gives enough space to fit a beam funnel (LEBT or MEBT) and to add quadrupoles for beam matching into the DTL