ess

EUROPEAN
SPALLATION
SOURCE

ESS Linac upgrade for ESSnuSB, and possible synergies

Workshop on Prospects for Intensity Frontier Particle Physics with Compressed Pulses from the ESS Linac

Uppsala, 2020-03-02—2020-03-03

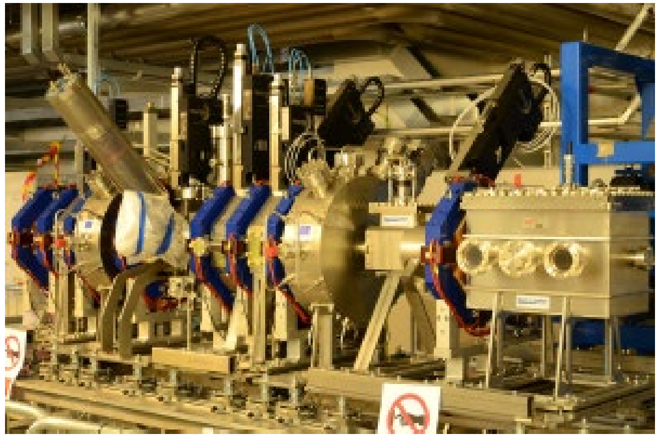
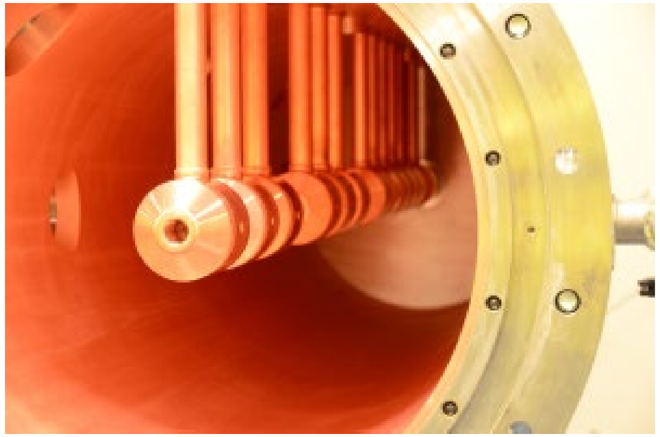
PRESENTED BY BJÖRN GÅLNANDER, ESS FOR WP2

2020-03-03

ESS overview

February 2020

ESS accelerator components

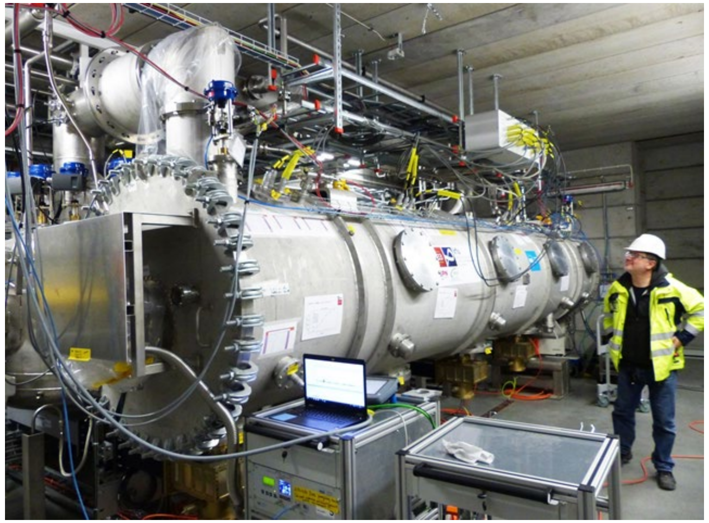

Yngve Levinsen

Commissioning of ion source and LEBT

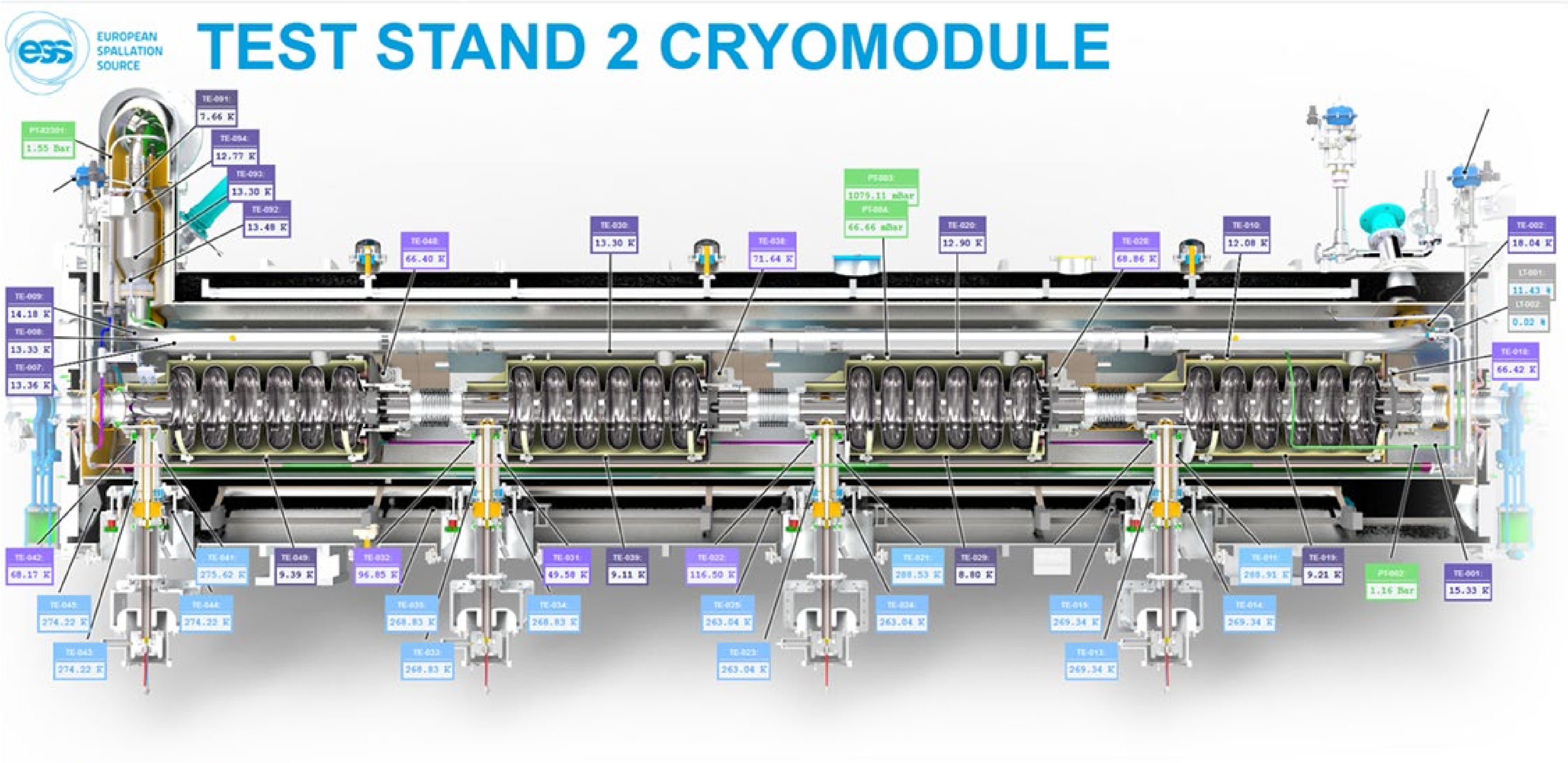
Beam commissioning 2018-2019

- In-kind contribution INFN
- Inauguration November 2018

Test stand 2 – cryomodule test



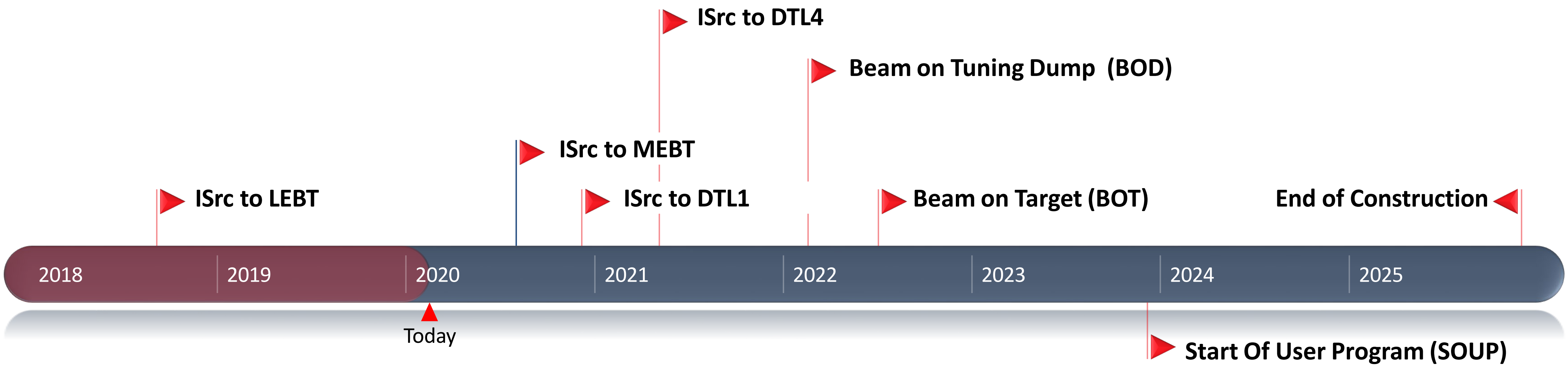
Recently, cooling down to 2 K



Credits: T. Grandsaert, N. Elias, H. Kocevar, T. Shea

ESS planning

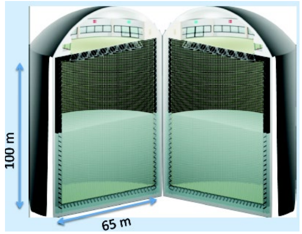
Big picture

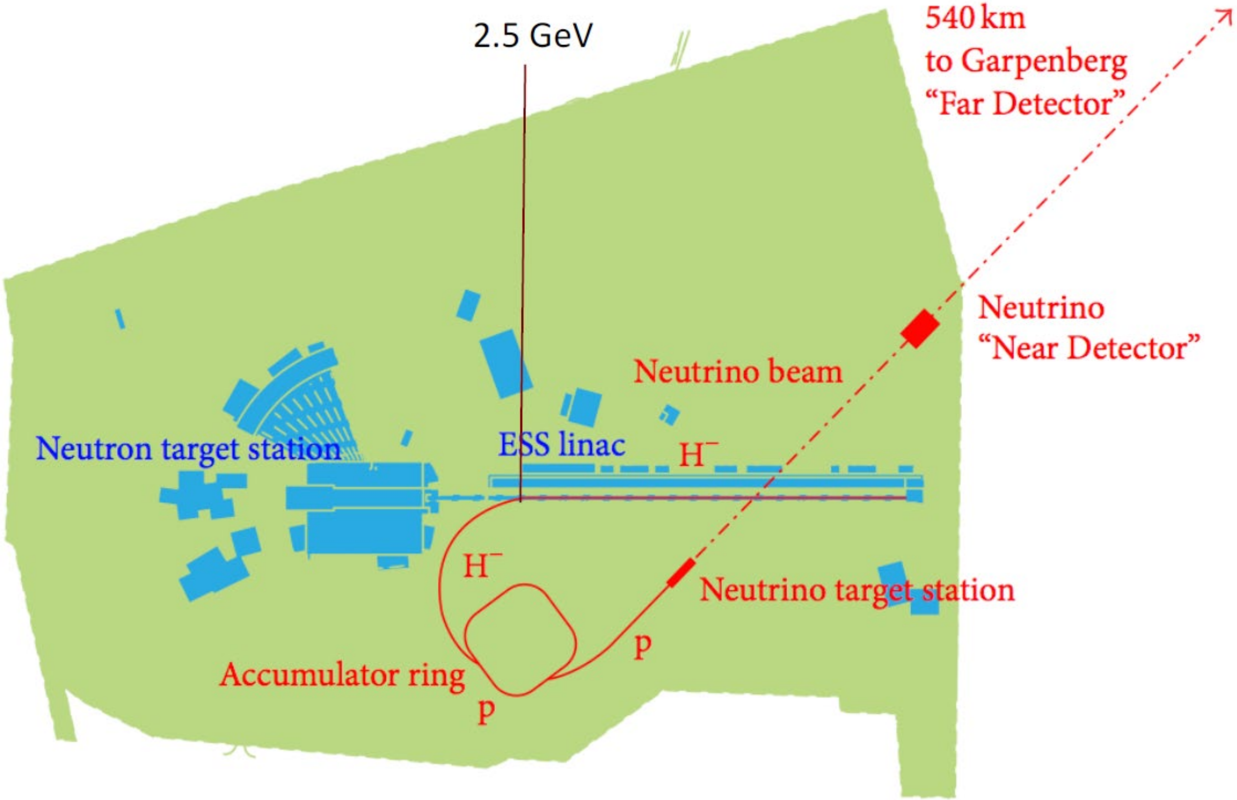


Ciprian Plostinar

ESS neutrino Super-Beam--ESSnuSB

ESS
NEUTRINO
SUPER BEAM





- Study CP violation by $\nu_\mu \rightarrow \nu_e$ oscillations
- Cherenkov detector in Garpenberg mine, 540 km north, at the second oscillation maximum.
- 5 MW for neutron production, **add** 5 MW to neutrino generation.

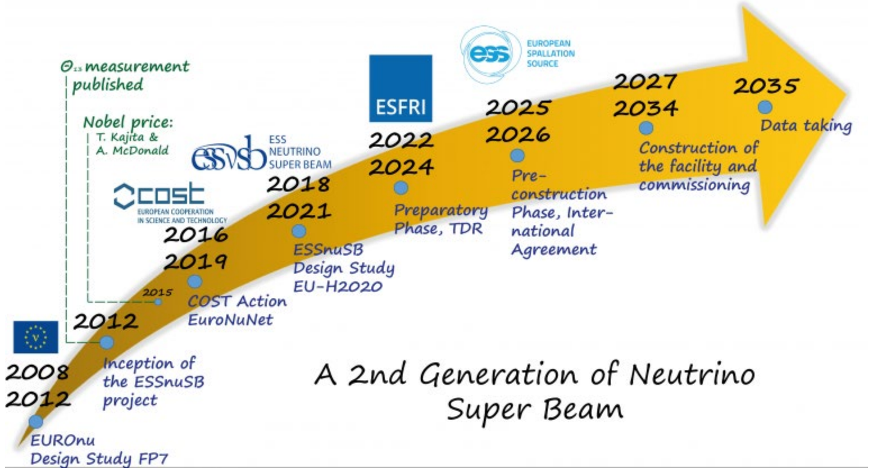
ESSnuSB

ESS NEUTRINO SUPER BEAM

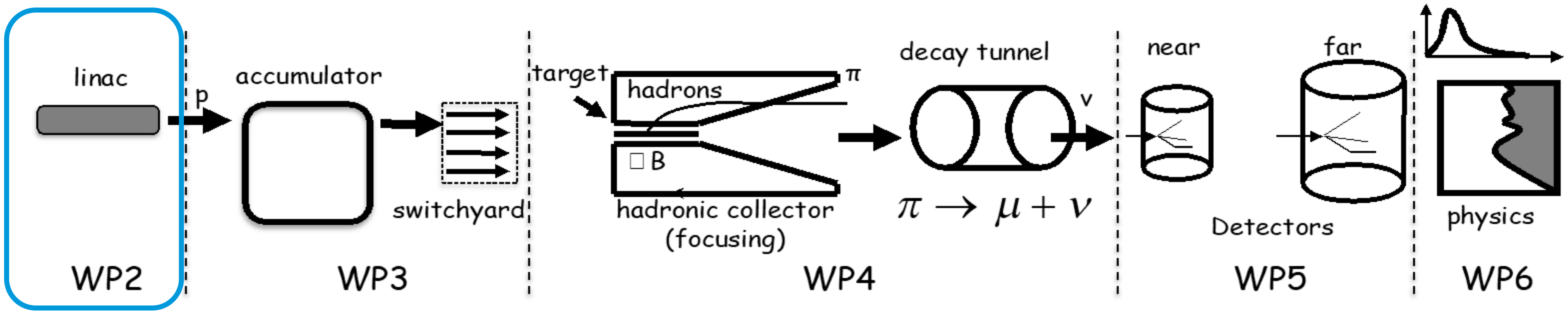
ESSνSB EU H2020 Design Study, 2018-2021

Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator

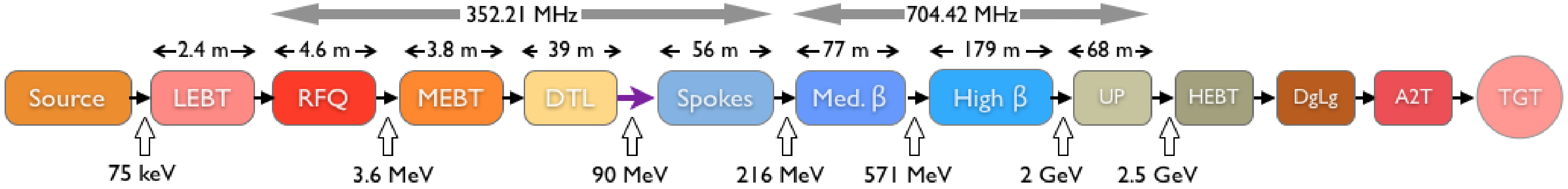
http://essnusb.eu



See Marcos Dragos, Monday



Linear accelerator

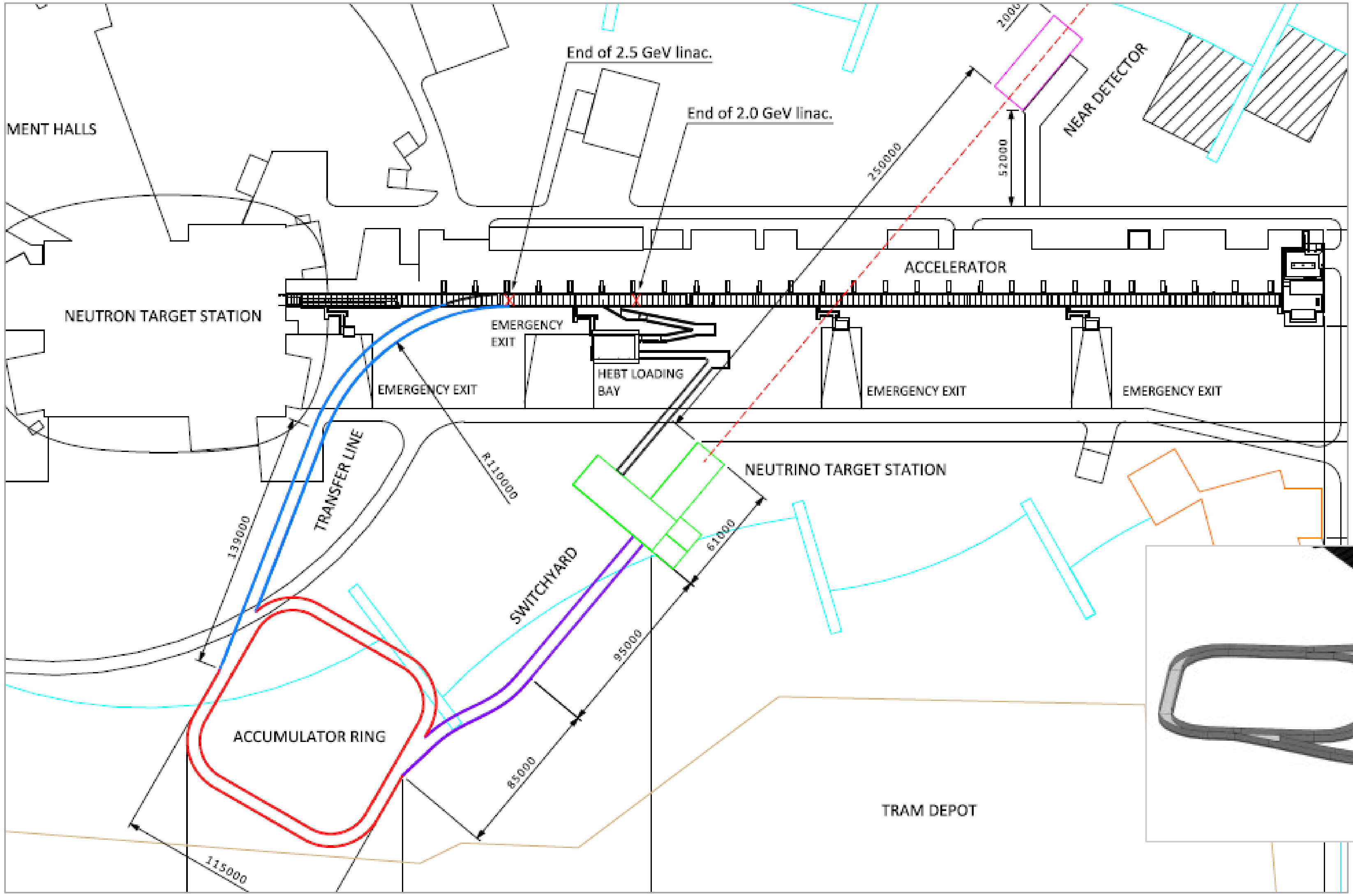


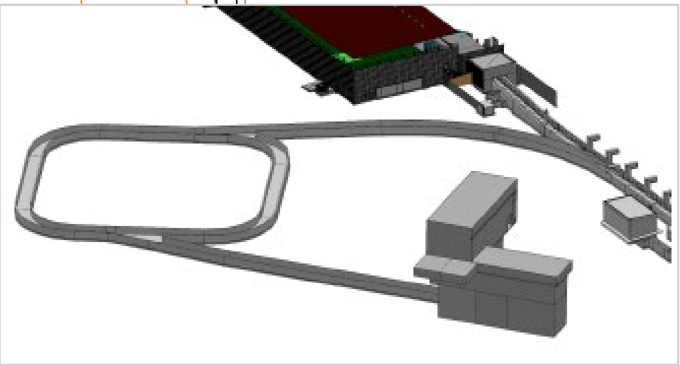
The accelerator layout, with normal conducting section and superconducting section. Indicated is the energy upgrade to 2.5 GeV.

Parameter	ESS	Upgrade ESSnuSB
Ion	p	p + H^-
Average beam power	5 MW	10 MW
Kinetic energy	2 GeV	2.5 GeV
Macro pulse current	62.5 mA	~50 mA
Macro pulse length	2.86 ms	>2.86 ms
Subpulse length	N/A	>0.75 ms
Pulse repetition rate	14 Hz	28 Hz (70 Hz)
Beam Duty cycle	4 %	8 %
Linac length	352.5 m	352.5 + ca 68 m

Beam parameters for ESS linac in standard mode and for the upgrade.

Layout ESSnuSB





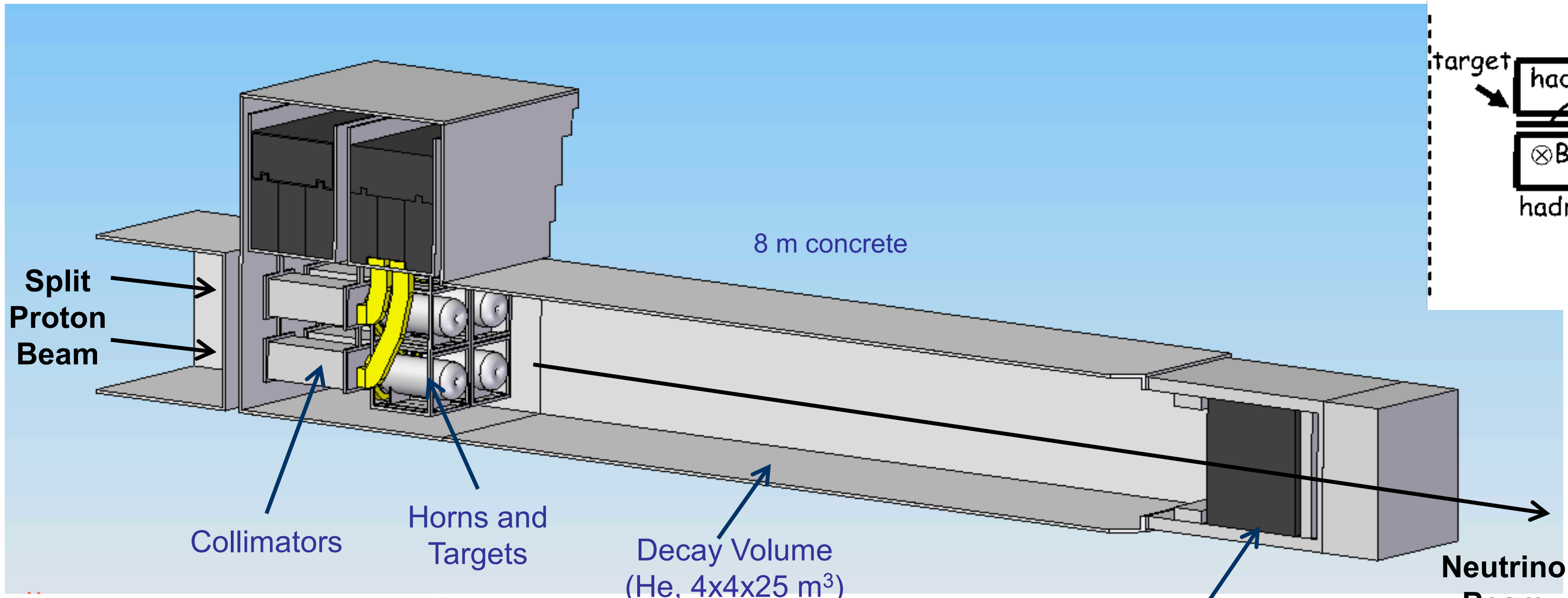
R. Johansson, N Gazis

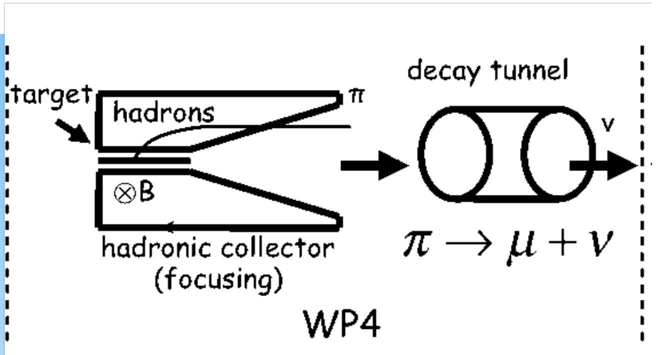
- 2.0 GeV ESS, 2.5 GeV ESSnuSB
- Transfer line design studied by Neven B. Kraljevich

See also talk by B. Kildetoft

Target station

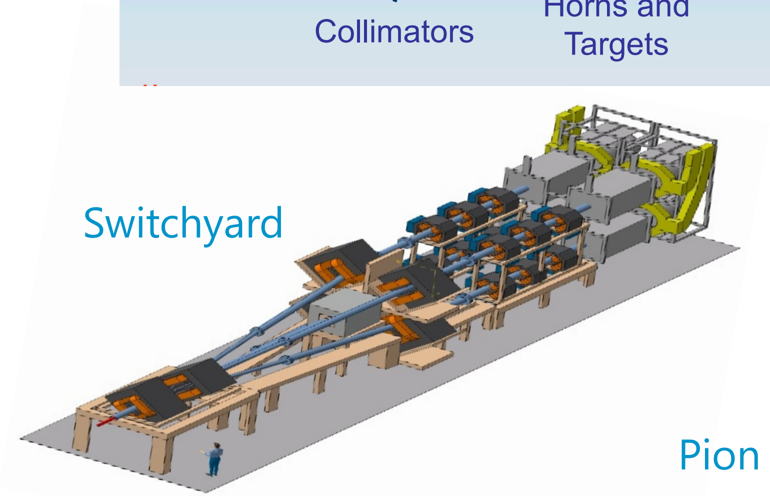
Adapted from EUROν

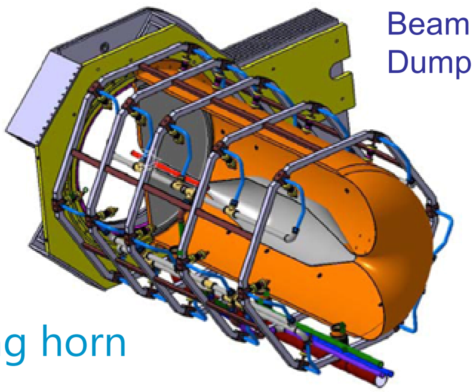




See talk by E. Baussan

Switchyard

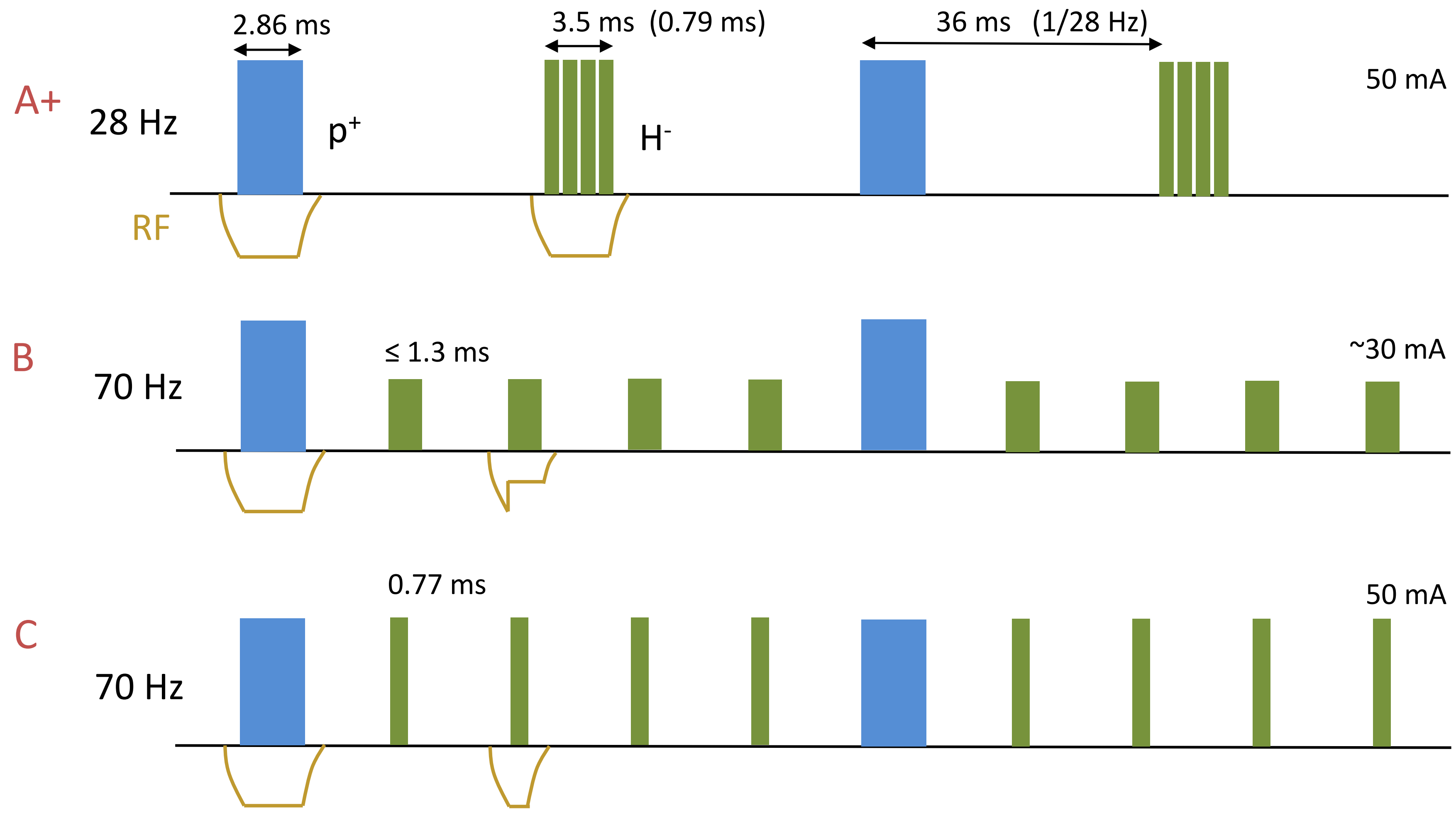




Pion focusing horn

- Short pulse requirement
- Limited flat top of focusing horn, 1.5 μs (heating)

Pulse structure options



Baseline
8.5 % beam duty cycle
10.5 % RF duty cycle

Preferred Linac

11.5% duty cycle
16% RF duty cycle

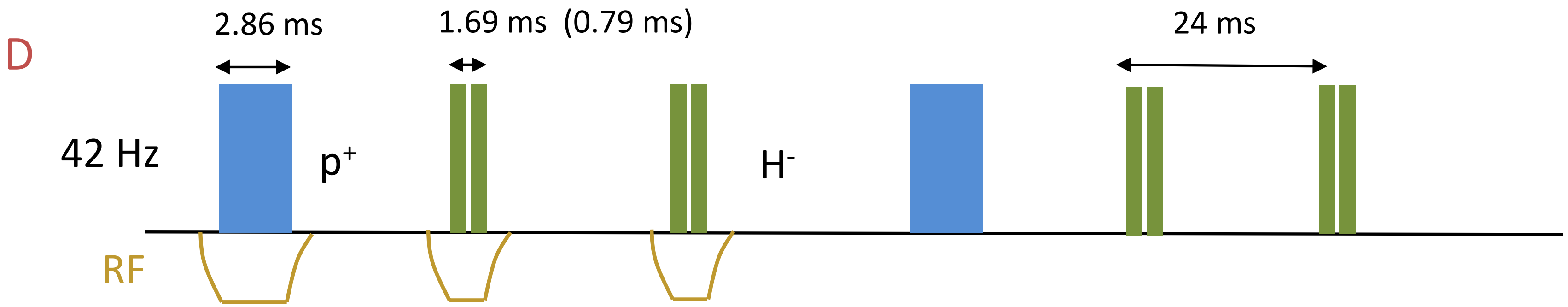
Lower current--reduced intrabeam stripping

8.5% duty cycle
13% RF duty cycle

70 Hz preferred accumulator, stripper foil heating, (And target focussing)

Pulse structure options

Alternative, since 3.5 ms pulse length is challenging for the H^- ion source



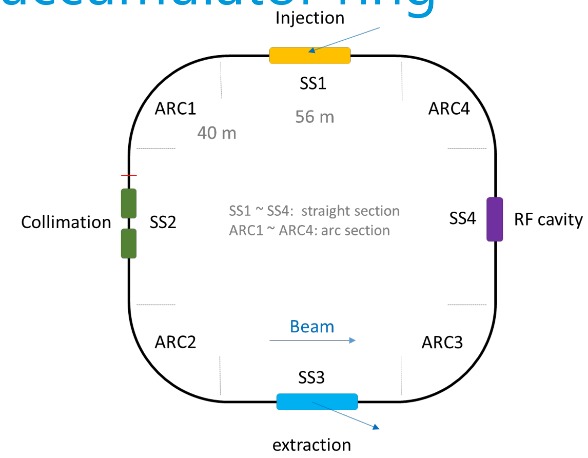
8.5% beam duty cycle
11.5% RF duty cycle

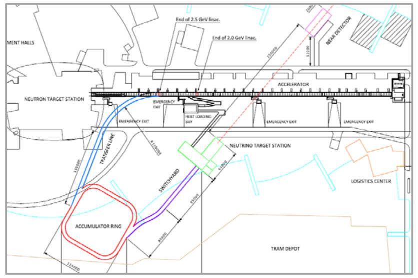
Advantageous for ion source and stripper foil (lower peak temperature)

Extraction gap in beam

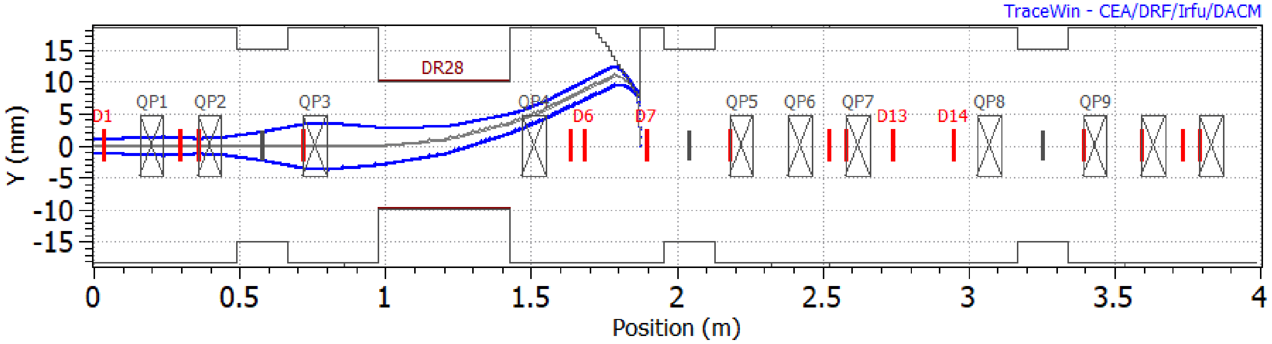
To avoid losses when extracting from the accumulator ring

- An extraction gap is needed to avoid beam loss while extraction kicker field is rising
- The extraction gap is created in the linac and preserved when stacking beam in the accumulator ring. The gap will be created by the chopper in the MEBT.
- The MEBT chopper is designed for a rise and fall time of < 10 ns.

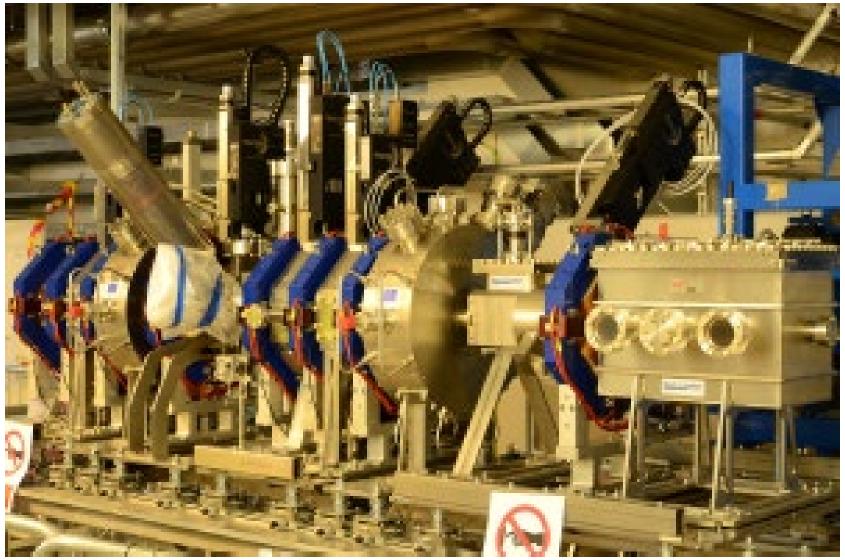




Accumulator ring, see talk by M. Olvegård, Ye Zou

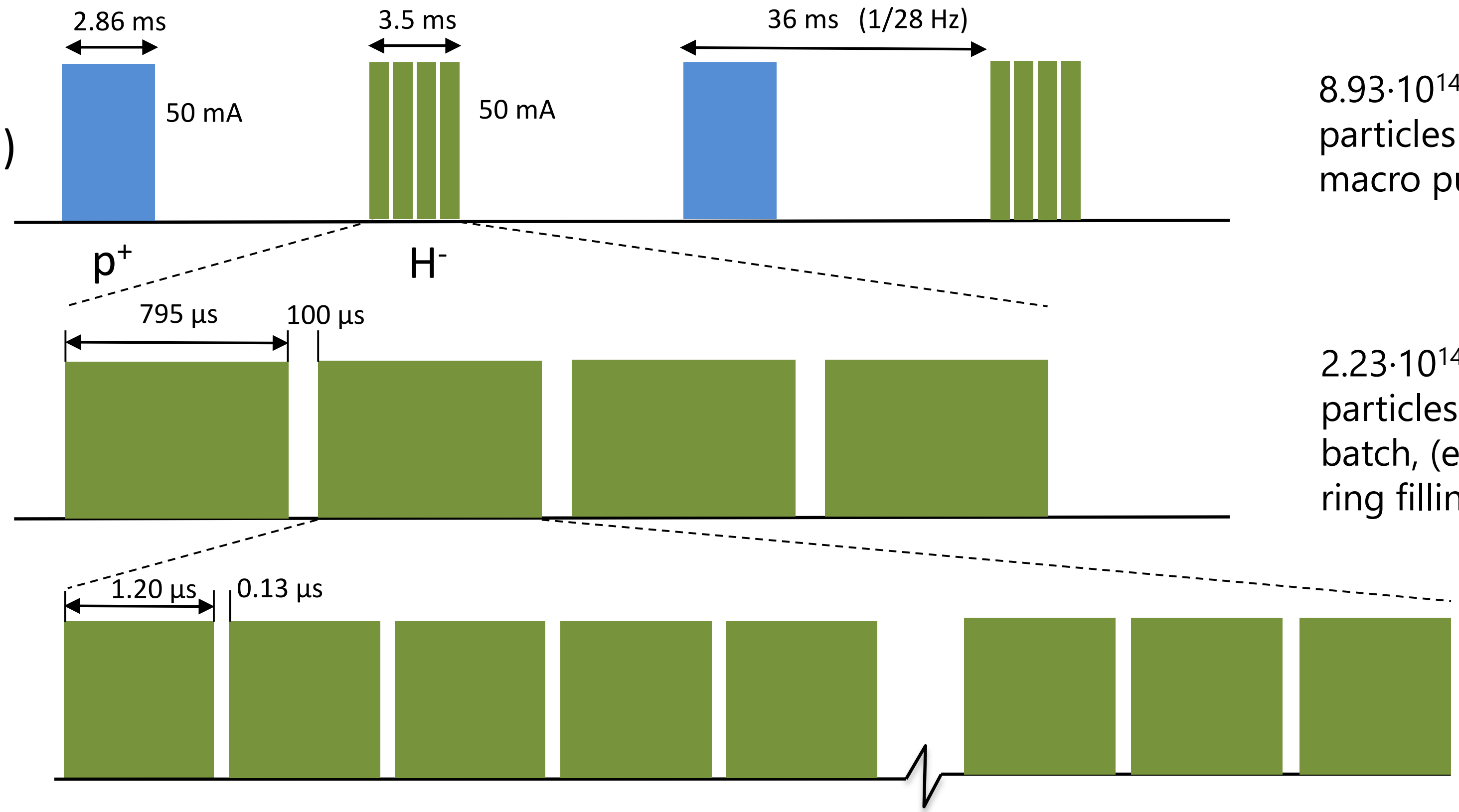


MEBT-Medium Energy Beam Transport



Extraction gaps--chopping

To avoid losses when extracting from the accumulator ring



28 Hz (RF)

$8.93 \cdot 10^{14}$ particles per macro pulse

Four batches with injection gap 100 µs. (extraction kicker fall time)

$2.23 \cdot 10^{14}$ particles per batch, (each ring filling) .

Extraction gaps 0.13 µs, (10%) (extraction kicker rise time)

597 pulses w. $3.74 \cdot 10^{11}$ particles.

Micro bunching, 352 MHz

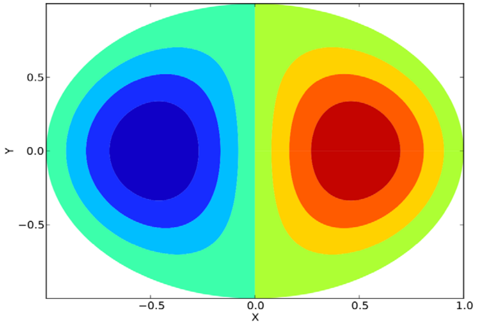
Pulse structure options

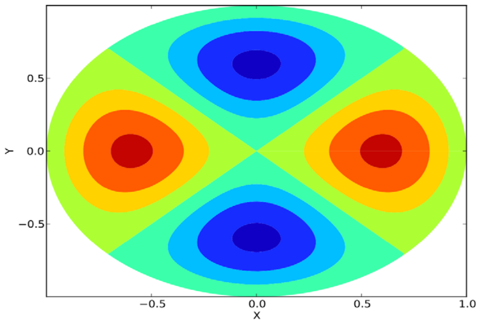
Beam parameters @ **2.5 GeV** for different schemes giving average power of 5 MW for H- (compensation for 10 % extraction gaps included)

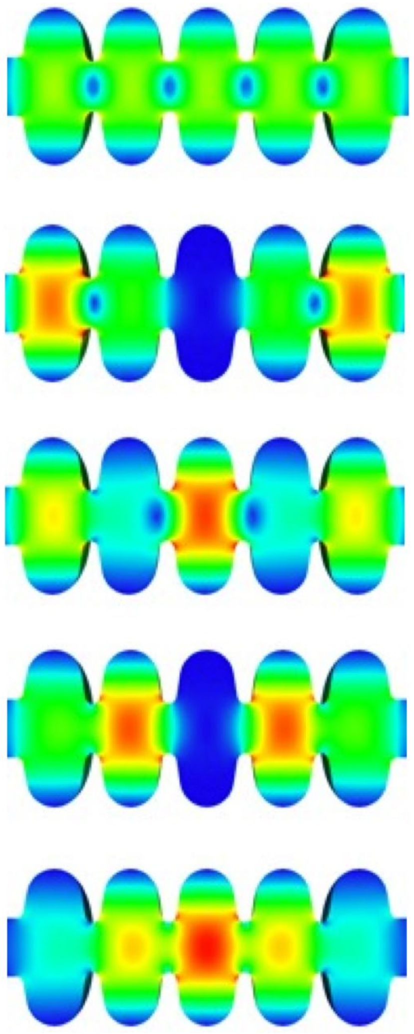
Scenario	**A+**	**B**	**C**
Current	50 mA	*30 mA*	*50 mA*
Particles per batch (extracted)	$2.23 \cdot 10^{14}$	$2.23 \cdot 10^{14}$	$2.23 \cdot 10^{14}$
Batch length (ms)	0.79(45)	*1.3*	*0.65*
Extraction gaps (μs)	0.13 (10%)	*0.13*	*0.13*
Frequency	14 Hz (1.12 kHz)	*70 Hz*	*70 Hz*
Length of macro pulse (ms)	3.48 (3.478)	*<1.3*	*0.79*
Number of batches	4	*4*	*4*
Length between pulses (ms)	32.5	*12.7*	*13.1*
Number of particles per macro period (72 ms / 14 Hz)	$8.93 \cdot 10^{14}$	$8.93 \cdot 10^{14}$	$8.93 \cdot 10^{14}$

Chopping – Higher order modes

- The high frequency chopping generates high frequency, which could excite HOMs / SOMs in the SC cavities.
- SOMs can cause cavity heating, leading to higher cryogenic load, and affect the beam dynamics. (ESS design does not include HOM couplers.)
- A study of the effects of the SOMs has been carried out.
- Alternatively create the extraction in the accumulator ring. But not trivial, too long time, instabilities.





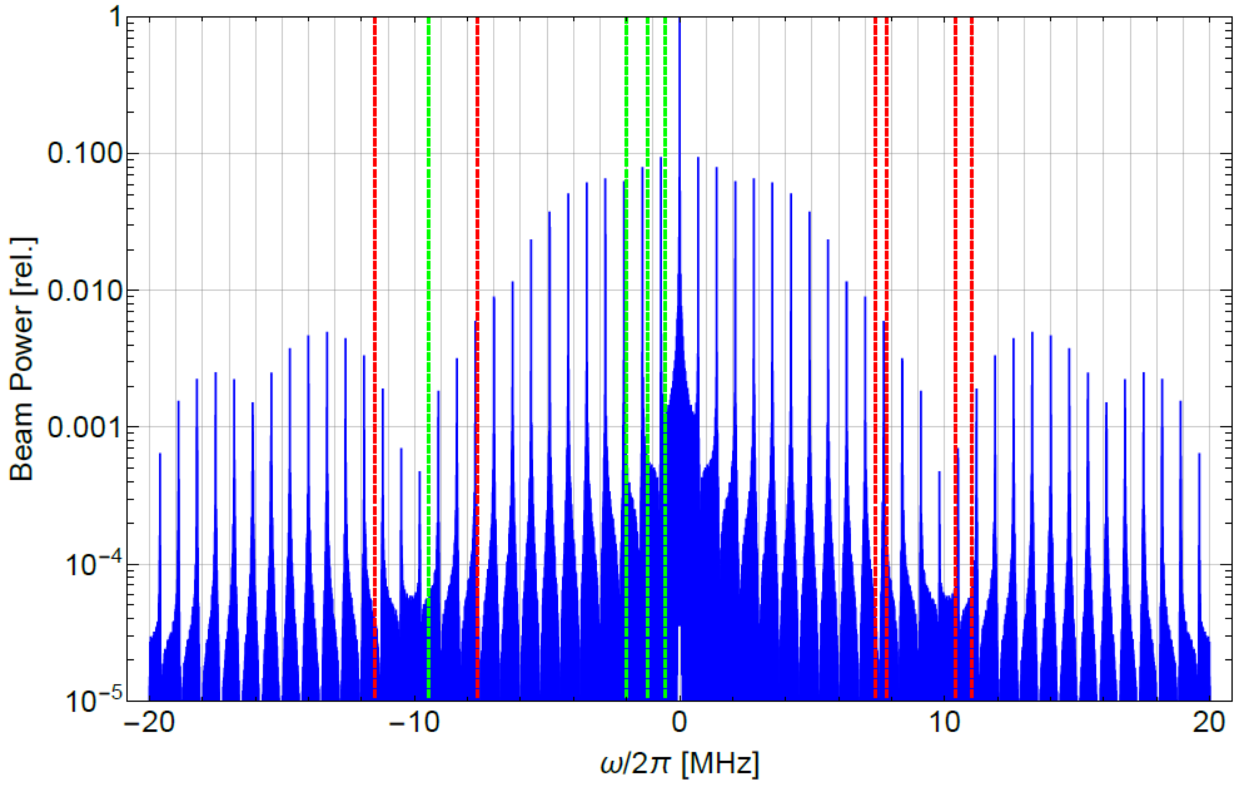


Effect of HOMs generated by chopping

- Creating extraction gap in the accumulator ring requires high frequency chopping in the linac, at 752 kHz (1.33 μs), can excite higher order modes (HOM)

- HOMs can cause cavity heating, leading to higher cryogenic load, and affect the beam dynamics. (ESS design does not include HOM couplers.)

Beam power spectrum with chopping



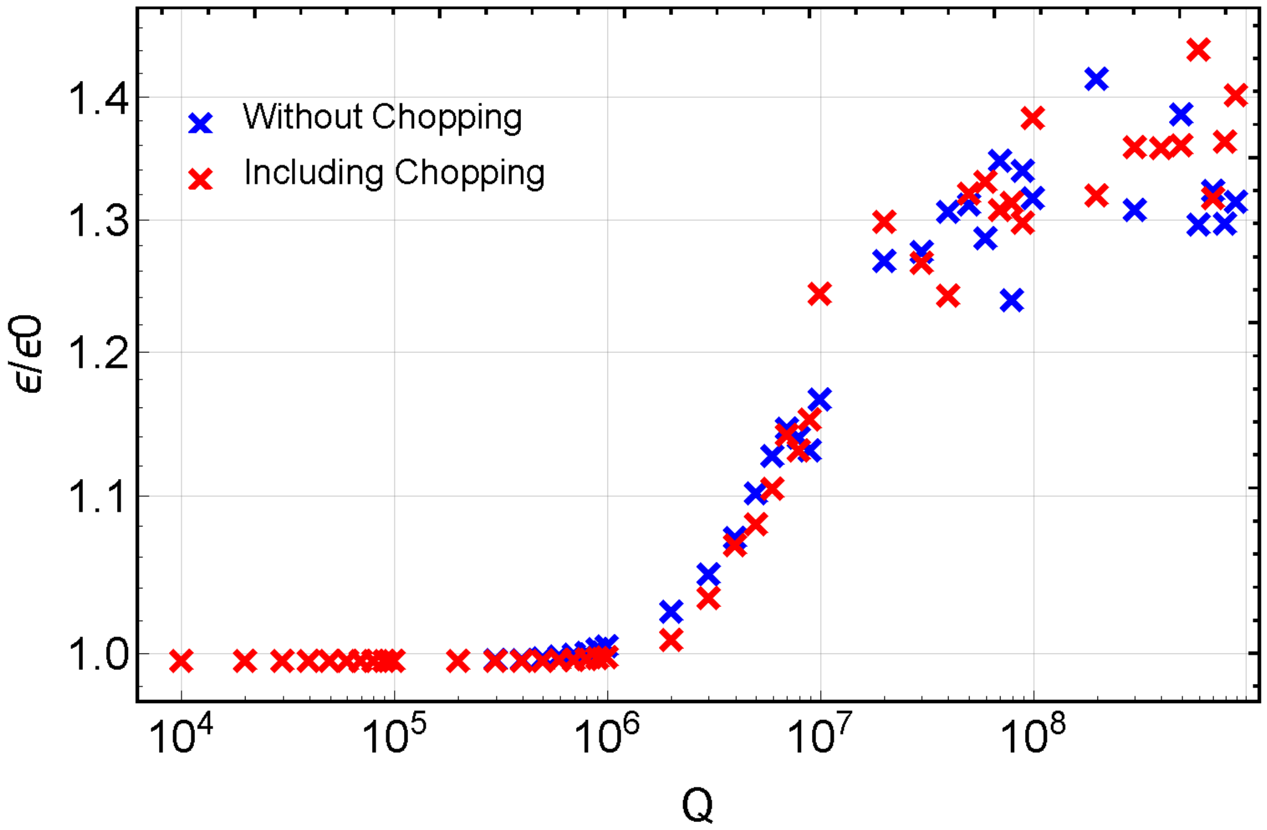
Center frequency 352 MHz, RF bunching frequency, HOMs are shown in red and the modes in the accelerating passbands in green.

Effect of HOMs generated by chopping

Simulations

- Simulations show no additional emittance growth from the beam chopping.
- Resonances are sufficiently far away from the excited frequencies.

Beam emittance growth vs Q-value



Aaron Farricker, IPAC 2020

Upgrade of linac components

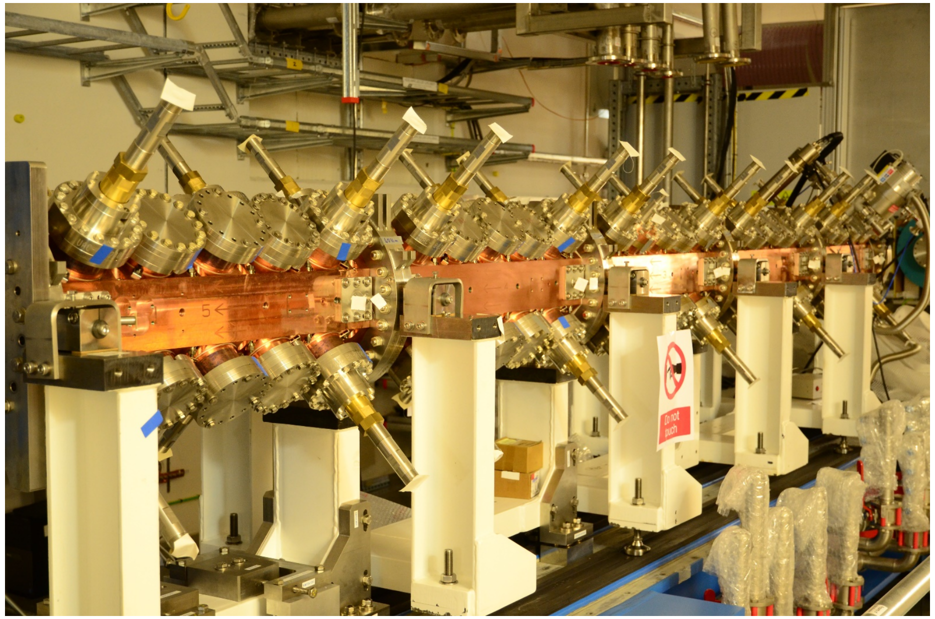
To cope with higher duty cycle, total power from 5 MW to 10 MW

- H^- ion source, pulse length
- RFQ, DTL, under investigation.
- Spokes, ellipticals,
- RF system, modulators—investigated, can be upgraded by adding capacitor chargers
- Klystrons-upgraded at the time of ESSnuSB
- Cryosystem, capable of handling increased RF duty cycle and dynamic heat load up to

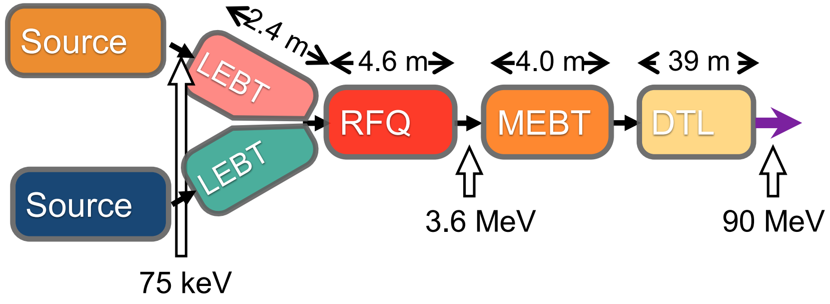
Linac front-end, normal conducting

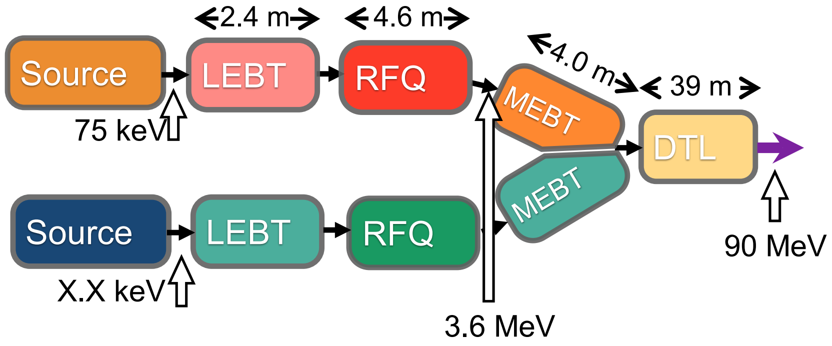
Ion source, RFQ and DTL

- RFQ accelerates the beam from 75 keV to 3.62 MeV.
- Present RFQ designed for RF duty cycle of 5%
- Under investigation if redesign or two separate RFQs



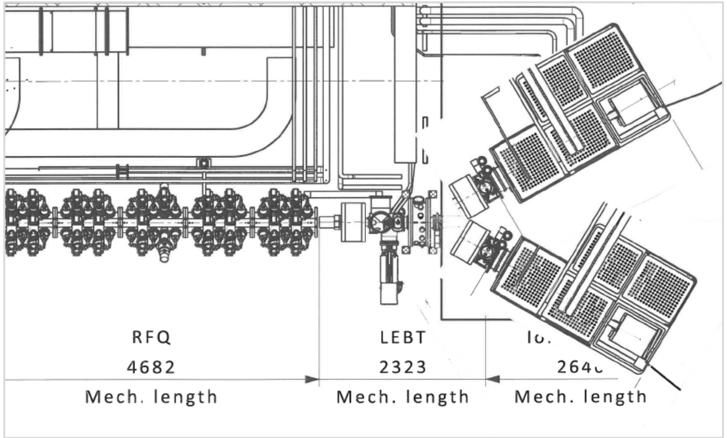
Merging H^- and proton beams



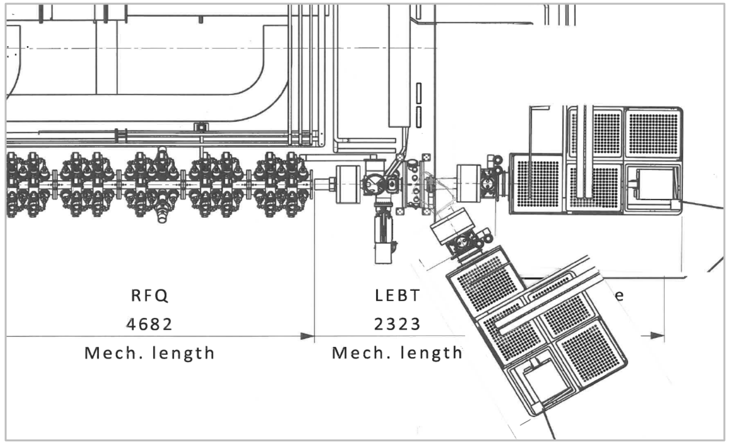


H⁻ ion source

Incorporation of ion source and modification of LEBT



30 degrees bending magnet, fixed field

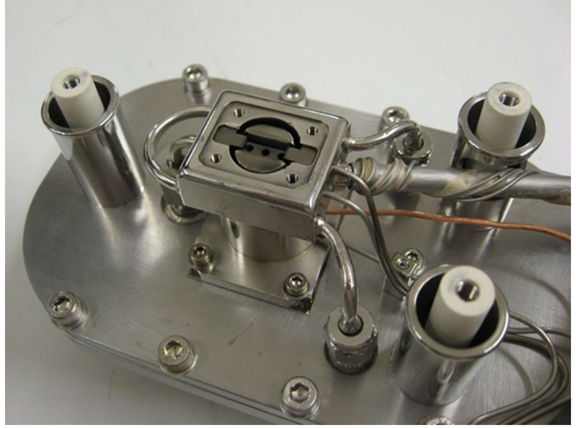


60 degrees bending magnet, switching

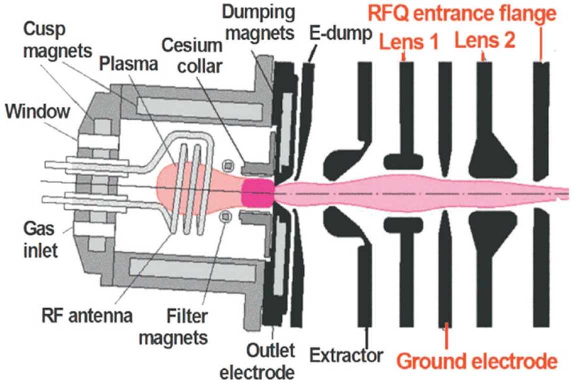
H^- ion source

Investigation of suitable ion source

Penning ion source, RAL



RF H^- ion source, SNS



Performance of existing ion sources

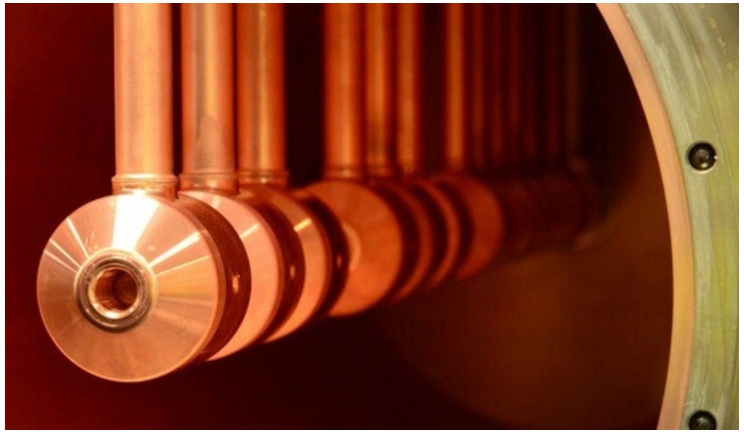
Parameter	RAL Penning 1X ISIS	RAL Penning 2X FETS	SNS, Oak Ridge, RF surface enhanced volume source
Beam pulse length (ms)	**0.25 ms**	**2 ms**	**1 ms**
Repetition frequency	50 Hz	50 Hz	60 Hz
Beam current	55 mA	100 mA	60 mA
Duty cycle	1.25%	10%	6%
Lifetime	5 weeks	2 weeks	14 weeks
Cs consumption	~0.7 g/week	~3.5 g/week	~2 mg/week
Emittance rms norm	0.25 π mm mrad	0.3 π mm mrad	0.25 π mm mrad
Emittance rms norm	0.7 π mm mrad	0.3 π mm mrad	N/A
Extraction voltage	18 (35) kV	18 (65) kV	65 kV

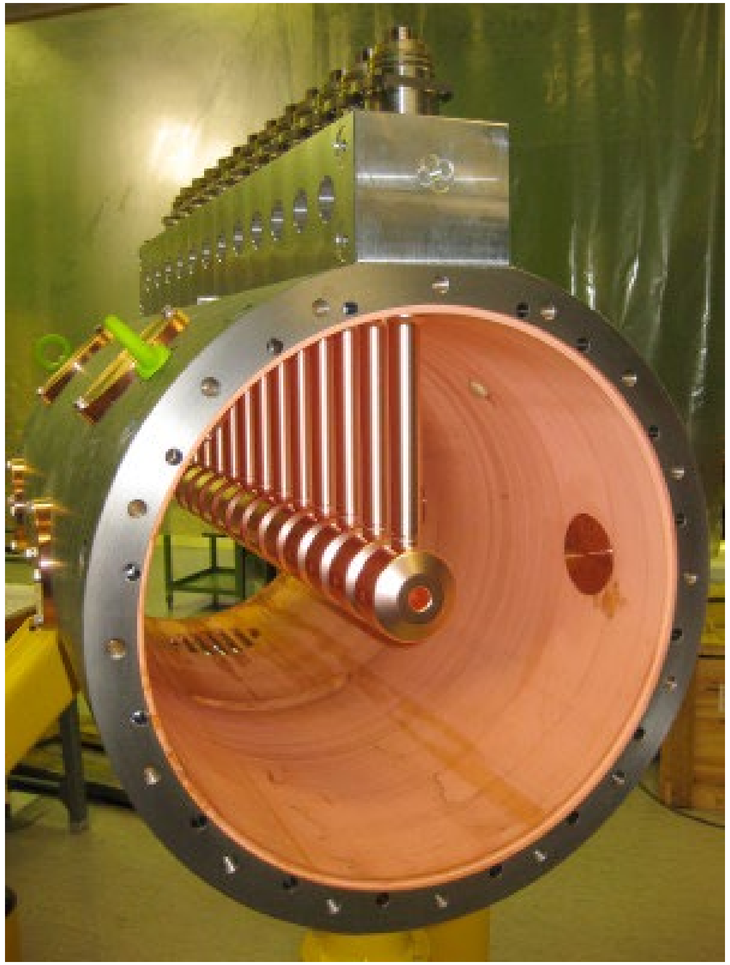
Requirement of ESSnuSB ion source 3.5 ms, 50 mA, 14 Hz (option A)

Tests of longer pulses, are ongoing at RAL; Discussions with SNS ongoing

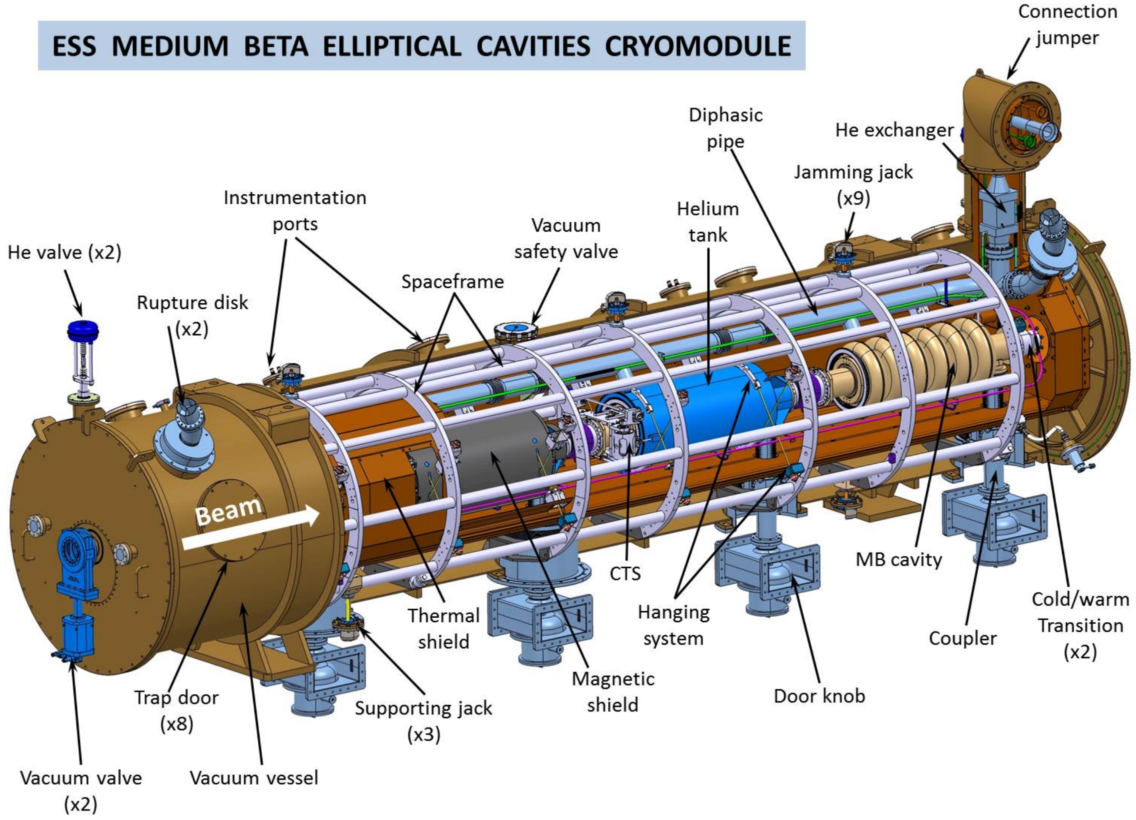
Drift Tube Linac

- The DTL is designed for a maximum duty cycle of 10%
- Under investigation if duty cycle can be extended >10%
- The coupler cooling should be enough for increased duty cycle





Cryo-system for supraconducting cavities



- The capacity of present ESS cryo-system is 3.0 kW at 2K
- Cooling demand of ESS baseline 14 Hz is 1.8 kW @ 2K
- The cooling demand when upgrading to ESSnuSB will be
  - -Option A (28 Hz) 3.2 kW @ 2K
  - -Option B (70 Hz), 4.3 kW @ 2K
  - -Option C (70 Hz), 3.8 kW @ 2K
- Option A, probably can be handled with the present cryo-plant. (margins in RF duty cycle, and Q-values probably better than in estimations)
- Option B and C, 70 Hz, needs upgrade of compressor ~30 M€
- Power couplers need to be tested for higher duty cycle

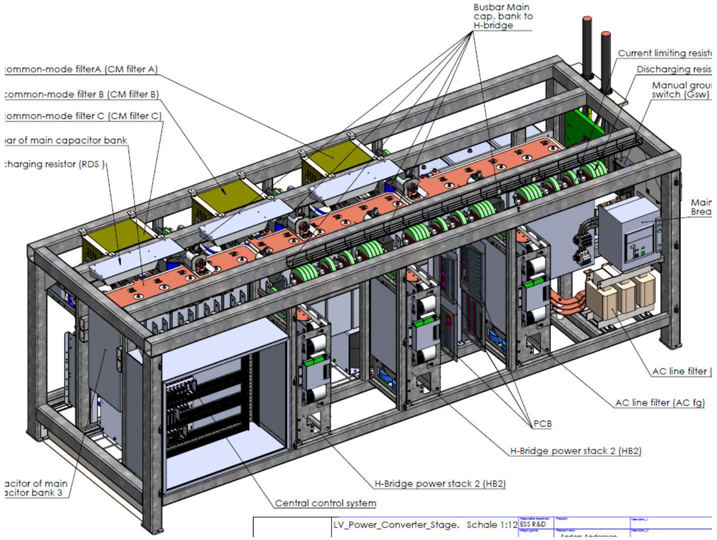
Upgrade of RF Modulators

Power supplies to the klystrons

Capacitor Charger

Capacitors and transformers

High voltage



Upgrade of RF modulators needed to meet the higher RF duty cycle (from 5% to 10-16%)

Upgrade of capacitor chargers of ESS modulators, Stacked Multi-Level (SML) topology, **feasible for all pulsing options. Lowest cost and footprint**

By Max Collins, Carlos Martins

H^- stripping

Binding energy of outer electron only 0.75 eV, easily stripped--can cause activation

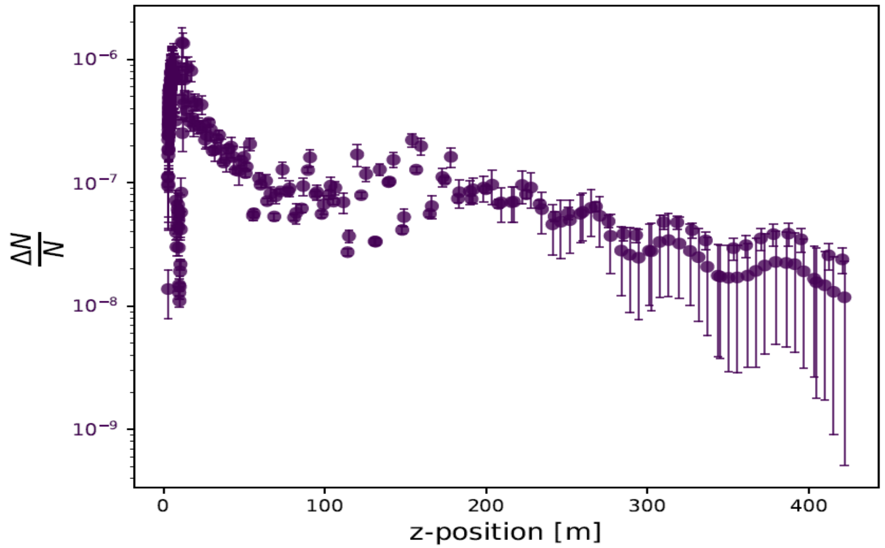
Stripping mechanisms

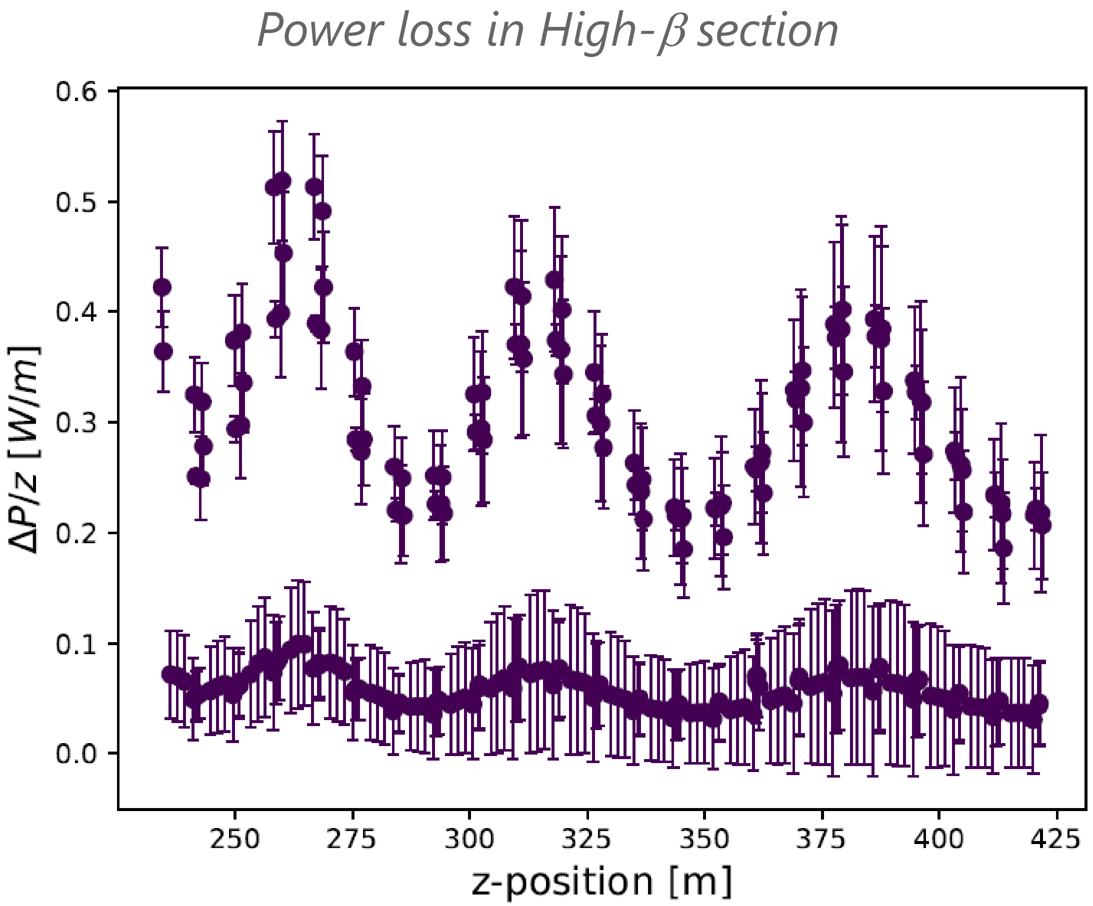
- Blackbody
  - Room temperature sectors, relativistic, beam transfer line
- Lorentz forces, magnetic fields
  - $E = \beta\gamma cB$, from magnetic fields. L
    Limitations in quad strength in linac, dipole field/bending radius in transfer line.
- Intra-beam stripping
  - Limitations on focusing, increase with particle density, release focusing
- Residual gas
  - Primarily in LEBT, but low power loss, due to low beam energy

Intrabeam stripping

Simulations of intrabeam stripping in ESSnuSB linac (2.5 GeV)

$$\frac{1}{N}\frac{dN}{ds} = \frac{N\sigma_{H^-}\sqrt{\gamma^2\theta_x^2+\gamma^2\theta_y^2+\theta_s^2}}{8\pi^2\gamma^2\sigma_x\sigma_y\sigma_s}F(\gamma\theta_x,\gamma\theta_y,\theta_s)$$





Conclusion: Intrabeam stripping power loss rate average about 0.15 W/m.
(0.5 W/m in the high-beta quadrupoles)

Ben Folsom, NuFACT 2019

Conclusions

- No showstoppers for upgrading linac from 5 MW to 10 MW
- Several beam pulsing options are being studied, 14 Hz, 3.5 ms H^- beam split in 4 batches is the baseline.
- Upgrade/adding of several components needed:
  H- ion source, RFQ, MEBT, cryo-system. Adding 8 cryo-modules for upgrade from 2.0 GeV to 2.5 GeV.
- Pulsing modes with RF duty cycle above 10% require more modifications, more costly. (cryo-compressor 30 M€)
- Upgrade of present modulators feasible for all pulsing options
- Stripping losses are on an acceptable level, and HOM due to beam chopping is not an issue.
- The linac design for ESSnuSB can serve as a powerful proton driver for different proposals in combination with a suitable accumulator ring for compressed pulses

Contributors—thanks!

WP2 ESSnuSB group members, colleagues at ESS and UU

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Neven Blaskovic Kraljevic, ESS, Postdoc

Aaron Farricker, CERN

Max Collins, LU, Carlos De Almeida Martins, ESS

Rasmus Johansson, Nick Gazis, ESS

Maja Olvegård, Ye Zou, WP3, UU

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

Extras

Sub-headline to strengthen the headline above

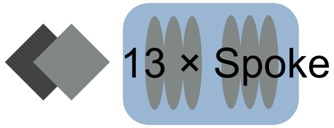
RF Duty Factor

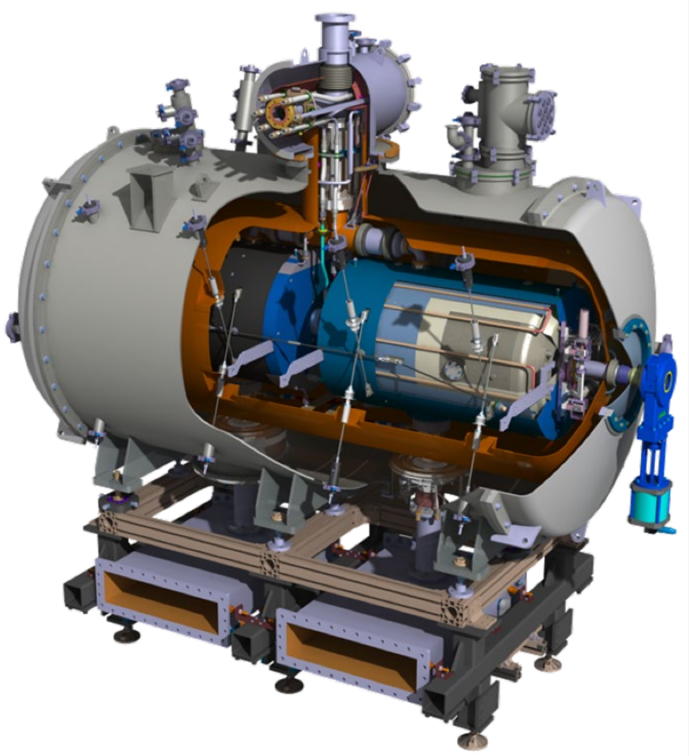
Scenario	A	A+	B	C	D
Proton beam	50 mA, 2.86 ms @14 Hz	50 mA, 2.86 ms @14 Hz	50 mA, 2.86 ms @14 Hz	50 mA, 2.86 ms @14 Hz	50 mA, 2.86 ms @14 Hz
H-	60 mA @ 14 Hz	50 mA @ 14 Hz	30 mA @ 70 Hz	50 mA @ 70 Hz	50 mA @ 42 Hz
H- beam pulse length (ms)	2.9 (0.65*4)	3.5 (0.79*4)	1.3 * 4	0.79 * 4	0.79 * 4
RF cavity field pulse length	3.5 + 3.5	3.5 + 4.0	3.5 + 2.0 * 4	3.5 + 1.4 * 4	3.5 + 2.5*2
RF duty factor (cavity)	10%	10.5%	13%	16%	11.5%
RF modulator pulse length (filling but not decay)	*3.2 + 3.2*	*3.2 + 3.8*	*3.2 + 1.7 * 4*	*3.2 + 1.1 * 4*	*3.2 + 1.1 * 4*

- In the duty factors above, the fill and decay times of the SC cavities are 0.3 ms. The field in the cavities thus is the beam pulse length plus 0.6 ms, which gives the RF duty cycle. (This is conservative, since the field is lower in the fill and decay phase.)
- The RF modulator pulse length, which is the required length of pulse from modulators is beam pulse length plus filling time, 0.3 ms. (not decay time))

Spoke

- Quadrupole Doublet Focusing (DC Quad and Corrector)
- Starts with a differential pumping section (LEDP)
- Accelerates the beam from 90 to 216 MeV
- Double spoke, βopt = 0.5, E_{acc} = 9 MV/m





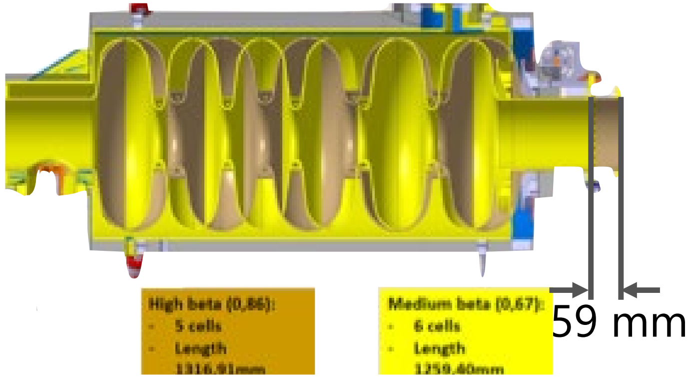
ESS Spoke cryomodule with two double spoke cavities, and two power couplers

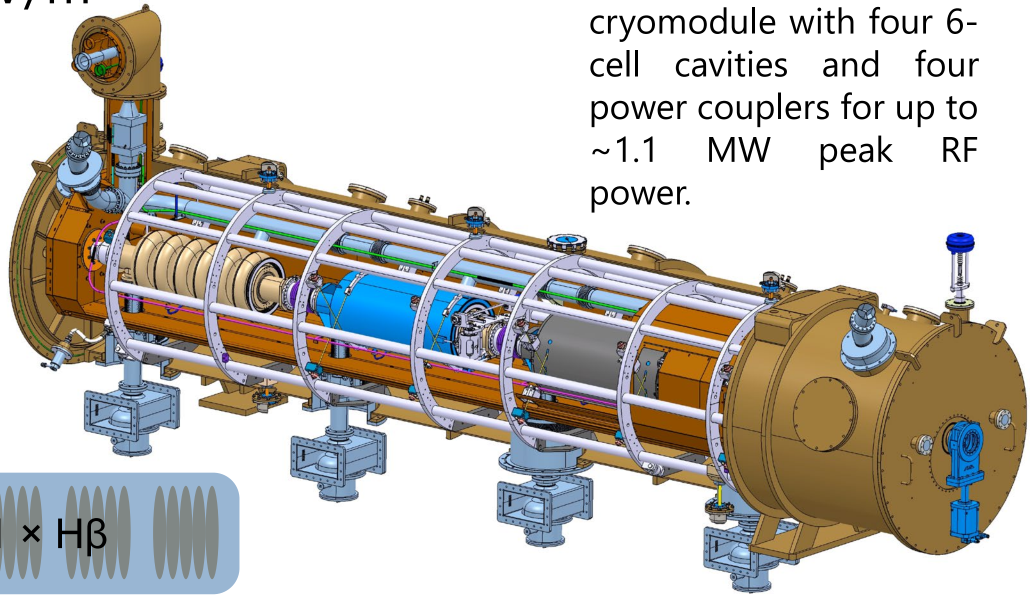
Ellipticals

- Quadrupole Doublet Focusing
- Accelerates the beam from 216 MeV to 571 to 2 GeV in Two families:

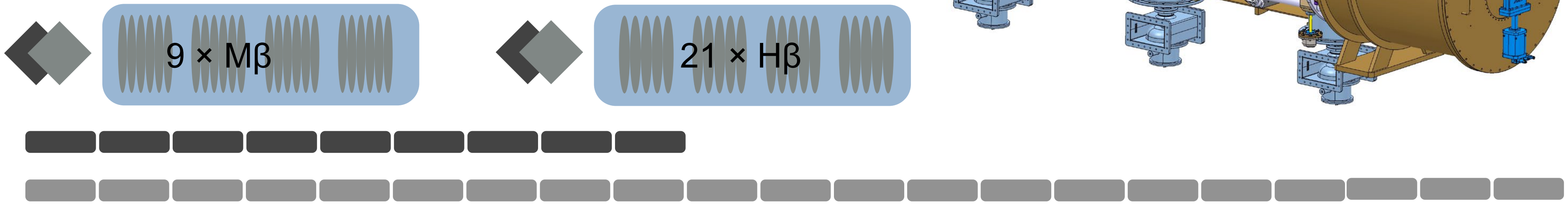
  6-cell, βg = 0.67, E_{acc} = 16.7 MV/m

  5-cell, βg = 0.86, E_{acc} = 19.9 MV/m





ESS elliptical cryomodule with four 6-cell cavities and four power couplers for up to ~1.1 MW peak RF power.



Linac modifications – overview

Sub-headline to strengthen the headline above

<table>
<tr><th></th><th>IS+LEBT</th><th>RFQ</th><th>MEBT</th><th>DTL</th><th>Spoke</th><th>Medium beta</th><th>High beta</th><th>High beta+</th></tr>
<tr><td>New device</td><td>New</td><td>~New</td><td>Modify</td><td>—</td><td>—</td><td>—</td><td>—</td><td>New</td></tr>
<tr><td>Cooling</td><td>—</td><td>Additional</td><td>Additional</td><td>Additional</td><td>Additional</td><td>Additional</td><td>Additional</td><td></td></tr>
<tr><td>Tunnel</td><td colspan="4">Device capacity / pipes / temperature</td><td colspan="4">Cryo-line/Cryomodule/Coupler/Waveguide</td></tr>
<tr><td>Gallery</td><td colspan="4">Cooling skids / Klystron cooling / pipes</td><td colspan="3">Klystron cooling / pipes / skids?</td><td>New</td></tr>
<tr><td>RF</td><td>—</td><td>Additional</td><td>Additional</td><td>Additional</td><td>Additional</td><td>Additional</td><td>Additional</td><td></td></tr>
<tr><td></td><td></td><td>Klystron</td><td>Amplifier</td><td>Klystron</td><td colspan="3">Tubes / LLRF</td><td>Klystron</td></tr>
<tr><td></td><td></td><td>Modulator</td><td>PC</td><td>Modulator</td><td colspan="3">Modulator / Power converters</td><td>Modulator</td></tr>
<tr><td>Cryo</td><td>—</td><td>—</td><td>—</td><td>—</td><td>Additional</td><td>Additional</td><td>Additional</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td colspan="4">Cryoline / Cryo plant</td></tr>
<tr><td>Magnets</td><td>Partially</td><td>—</td><td>Partially</td><td>—</td><td colspan="4">Corrector</td></tr>
</table>

2020-03-03