Upgrade possibility of the ESS linac for the ESSnuSB project

Björn Gålnander, ESS

On behalf of WP2 of ESSnuSB Collaboration

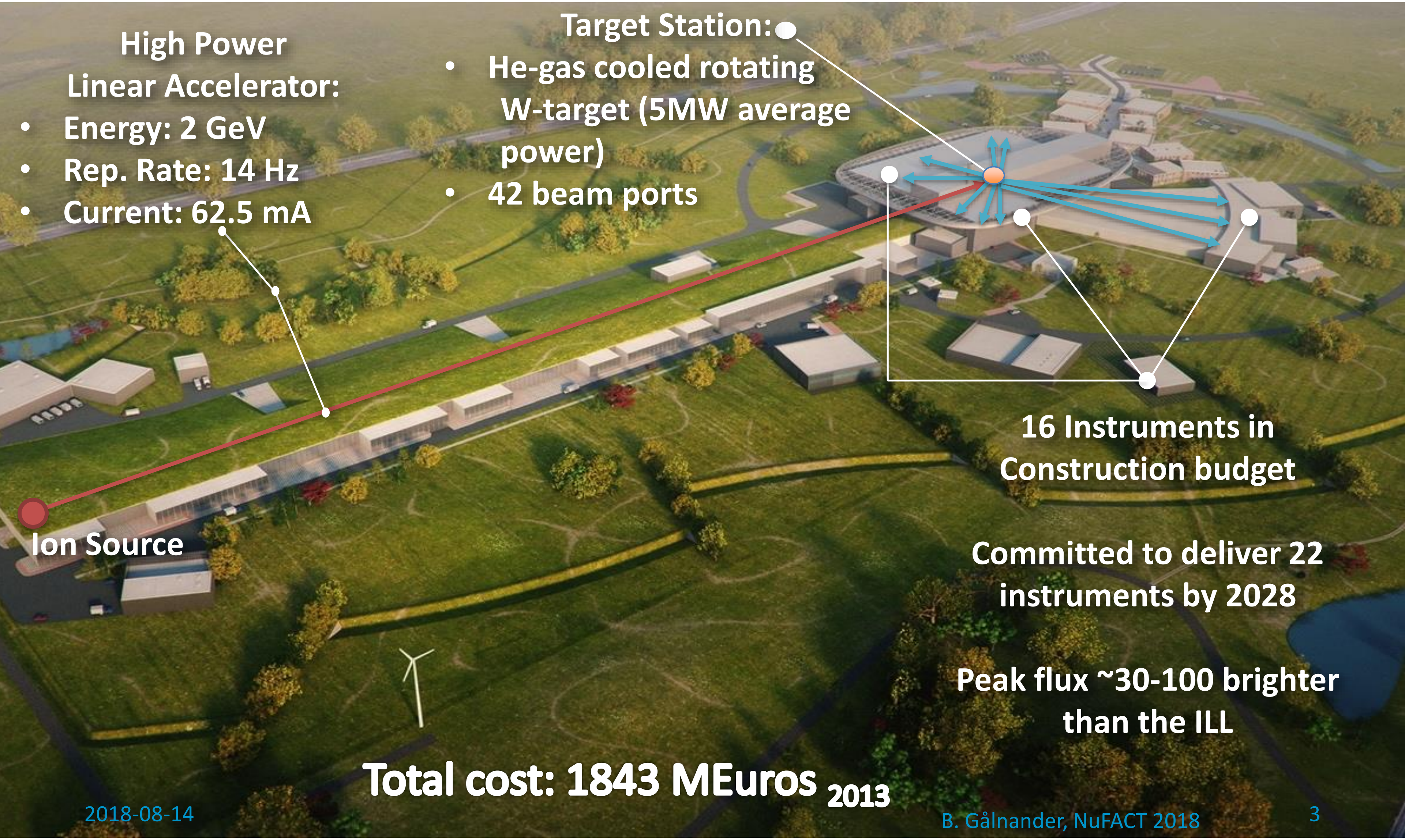
2018-08-14

NuFACT 2018, Blacksburg, Virginia

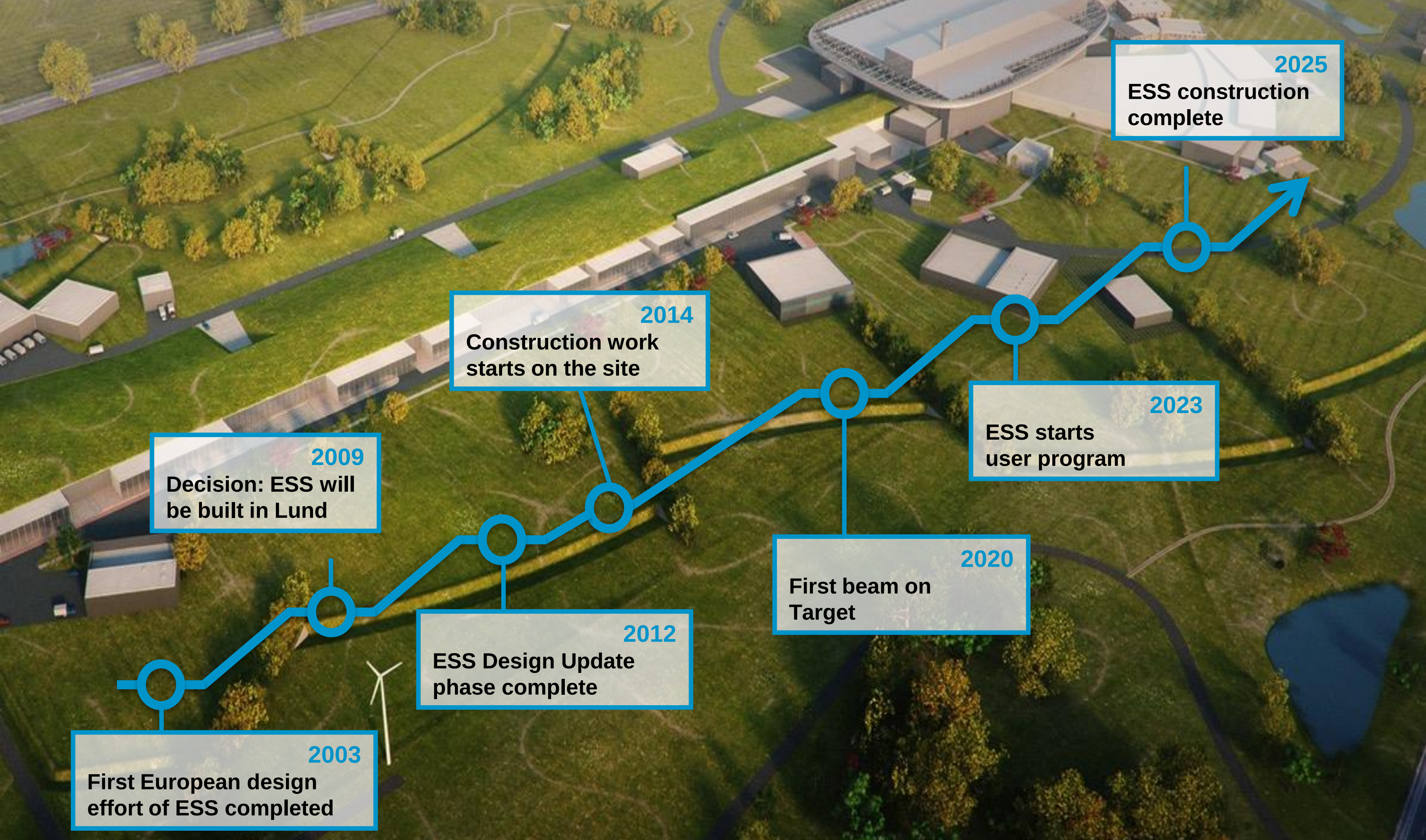
Outline

- Status of ESS
- ESSnuSB project
- Upgrade issues of the accelerator
- Extraction gap pulsing structure -- SOM simulations

ESS design


High Power
Linear Accelerator:
• Energy: 2 GeV
• Rep. Rate: 14 Hz
• Current: 62.5 mA
Target Station:
• He-gas cooled rotating W-target (5MW average power)
• 42 beam ports
16 Instruments in
Construction budget
Committed to deliver 22
instruments by 2028
Peak flux ~30-100 brighter
than the ILL
Ion Source
Total cost: 1843 MEuros 2013

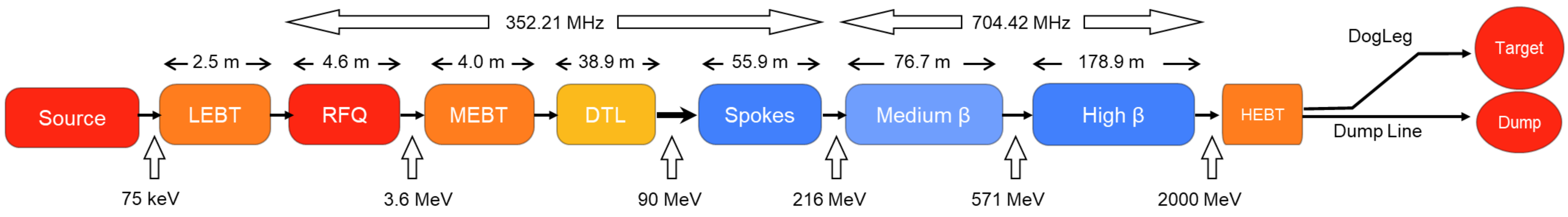
Journey to deliver the world’s leading facility for research using neutrons



Present status of the ESS project

June 2018

Accelerator



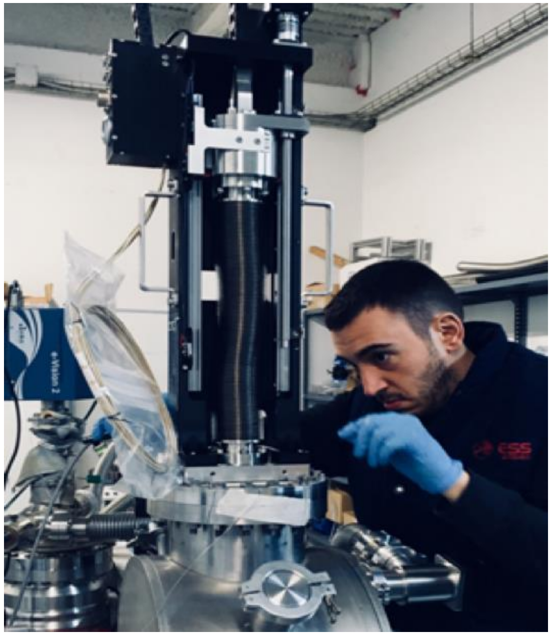
	Length (m)	No. Magnet	#Cav x βg/(Opt)	No. Sections	Power (kW)	IK partner
LEBT (from Plasma)	2.7	2 Solenoids	—	1	—	INFN-LNS
RFQ	4.5	—	1	1	1600	CEA Saclay
MEBT	4.0	11 Quads	3	1	15	ESS-Bilbao
DTL	38.9		5	5	2200	INFN-LNL
LEDP + Spoke	55.9	26 Quads	26 x (0.50)	13	330	IPNO
Medium Beta	76.7	18 Quads	36 x 0.67	9	870	LASA / CEA
High Beta 1 (~1.3 GeV)	93.7	22 Quads	44 x 0.86	11	1100	STFC / CEA
High Beta II	85.2	20 Quads	40 x 0.86	10	1100	STFC / CEA
Contingency + HEDP	132.3	32 Quads	—	15	—	Elettra
DogLeg	64.4	12 Quads + 2 Dipoles	—	1	—	Elettra
A2T	44.7	6 Quads + 8 Raster	—	1		Aarhus Uni
	603.0					

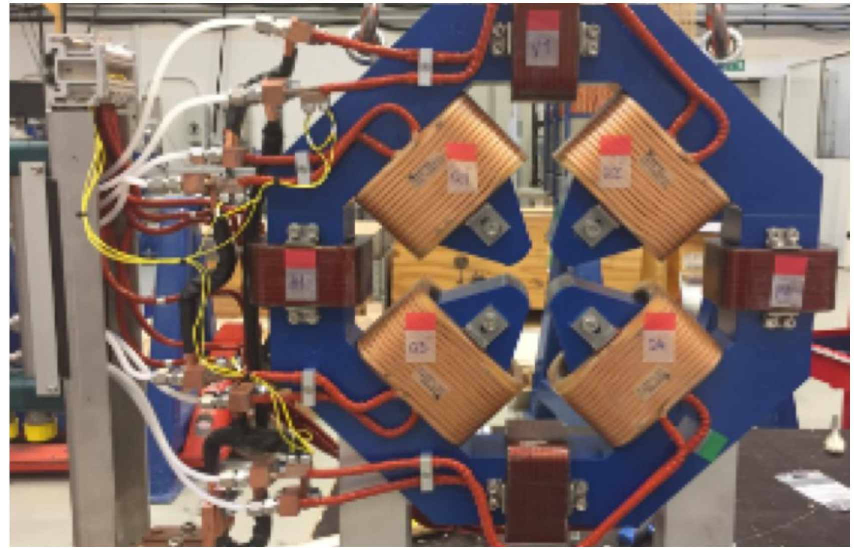
Ion Source / LEBT

- ISrc & LEBT hardware installed
- ISrc safety fence installed
- Racks & electronics installed (except chopper)
- Cable pulling done
- Cable terminations being finalized
- Grounding to be done
- Racks not powered yet (some temporarily)
- Water-cooling skid delivered
- Hardware testing will start soon.

Courtesy:
Edgar Sargsyan

MEBT





Courtesy:Danfysik

Buncher

Chopper

DTL – Drift Tube Linac

- Bead pulling and tuning on DTL Aluminum model (Tank #2 as mock-up) on-going in Legnaro

- DTL Tank 4 section 1 at the GSI copper plating facility

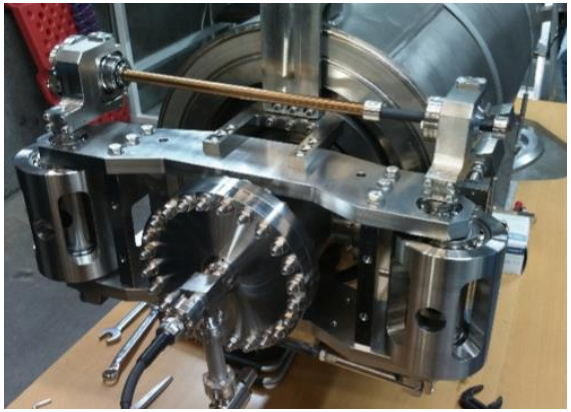
Spoke Cavities SC

First pair of ESS series spoke cavities, March 2018

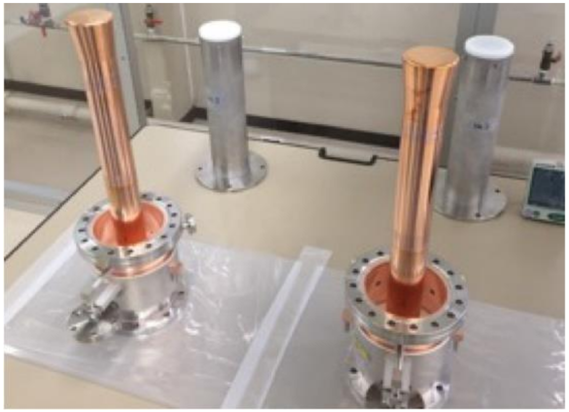
Series production on-going at Zanon

Elliptical Cavities SC

Coupler-cavity assembly stand



Assembly and adjustment of the cold tuning systems



Main power couplers conditioned for up to 1.1 MW at travelling waves and reflection

String of cavities for M-ECCTD

Pre-series thermal shield

Pre-series space-frame

AARHUS UNIVERSITY

Beam Delivery System

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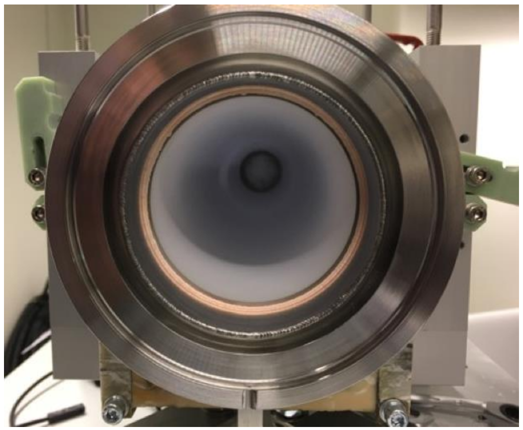
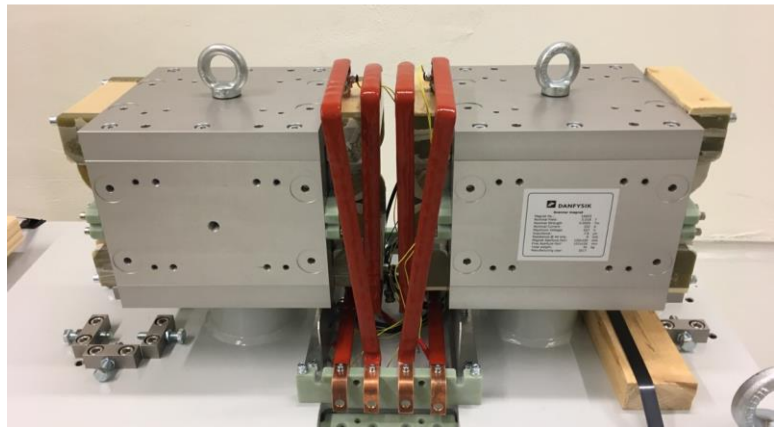
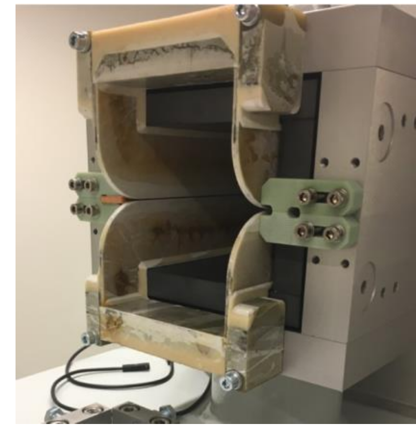
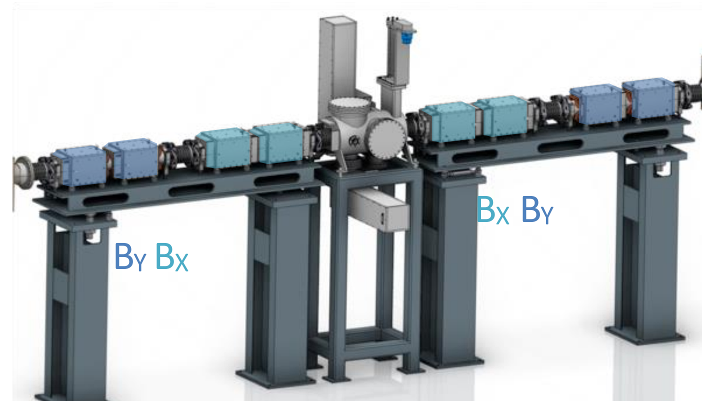




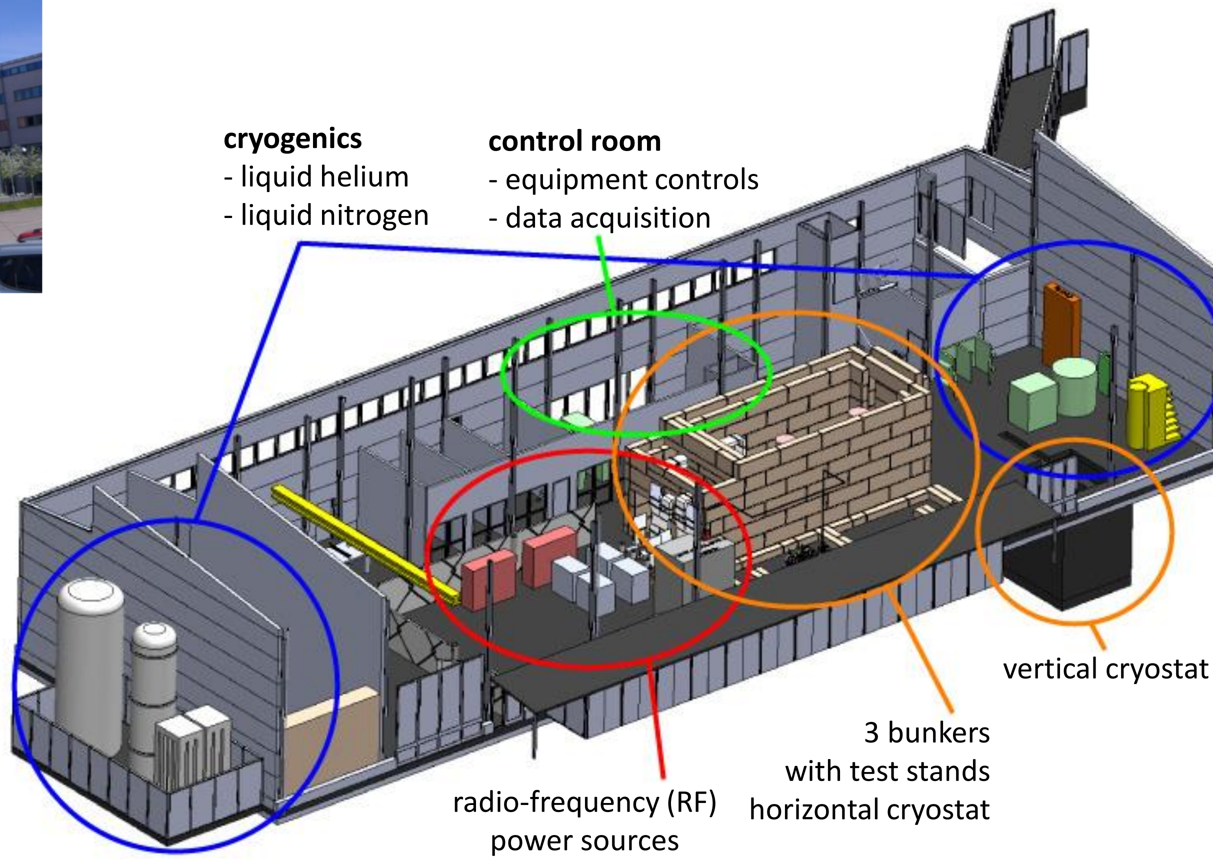




UPPSALA UNIVERSITET

EUROPEAN SPALLATION SOURCE

Facility for Research Instrumentation and Accelerator Development



Courtesy: Roger Ruber

Status ESS Tests at FREIA

- **Double spoke resonator**
  - equipped with power coupler and tuner
- **High-beta elliptical cavity**
  - equipped with power coupler and tuner
  - testing to continue after summer break
- **Spoke cryomodule**
  - expected on 15 August
- **Spoke RF station**
  - developed 2 prototypes
  - up to 28 Hz pulse rate (for upgrade)
- **Elliptical RF Station**
  - prototype modulator acceptance test
  - klystron & RF distribution testing

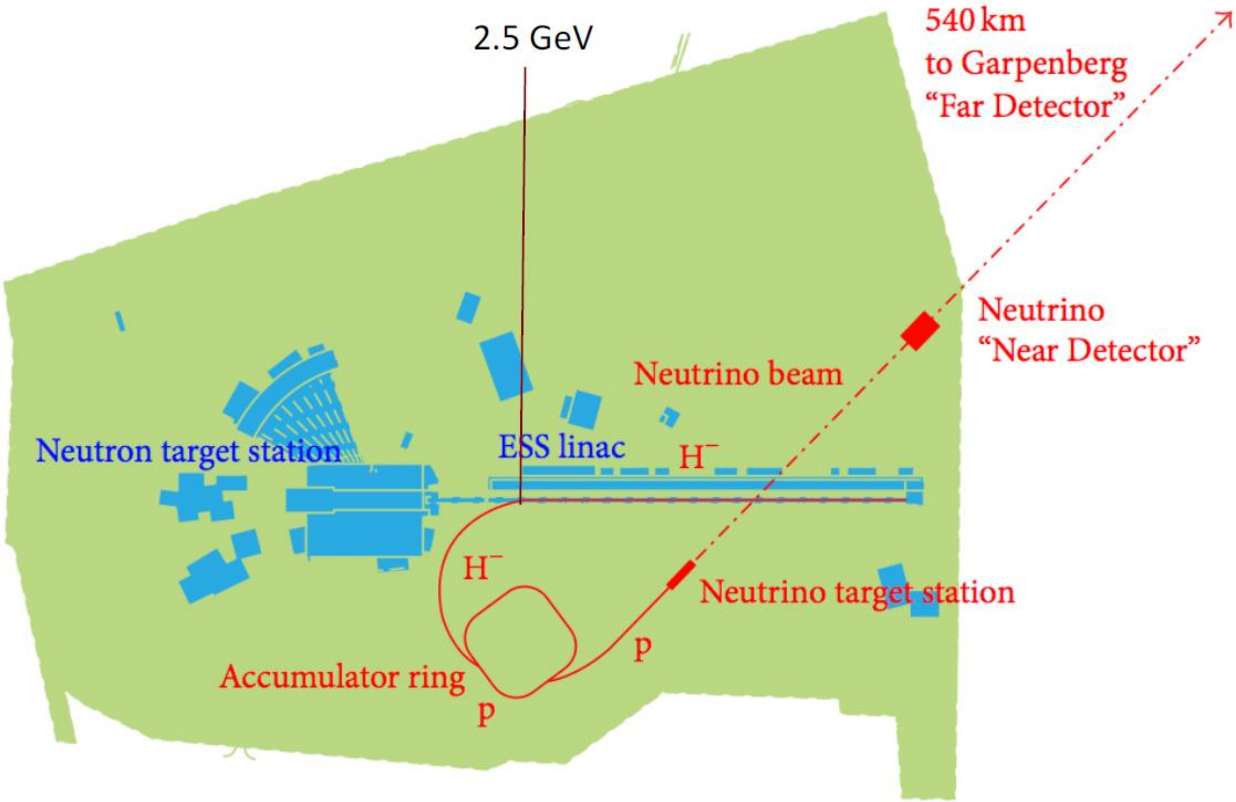
Courtesy: Roger Ruber

Status summary

- Construction of the accelerator buildings is finished
  - Target and Instrument halls have a good progress
- Project is at 50% completion
  - Ion Source and LEBT are installed and under commissioning.
  - Major pieces are arriving for installation in the Klystron Gallery and the Tunnel

ESS neutrino Super-Beam--ESSnuSB

ESS NEUTRINO SUPER BEAM



- Detector in Garpenberg mine, 540 km north, at the second oscillation maximum.
- 5 MW for neutron production, **add** 5 MW to neutrino generation.

ESS Neutrino Super Beam Project

ESS NEUTRINO SUPER BEAM

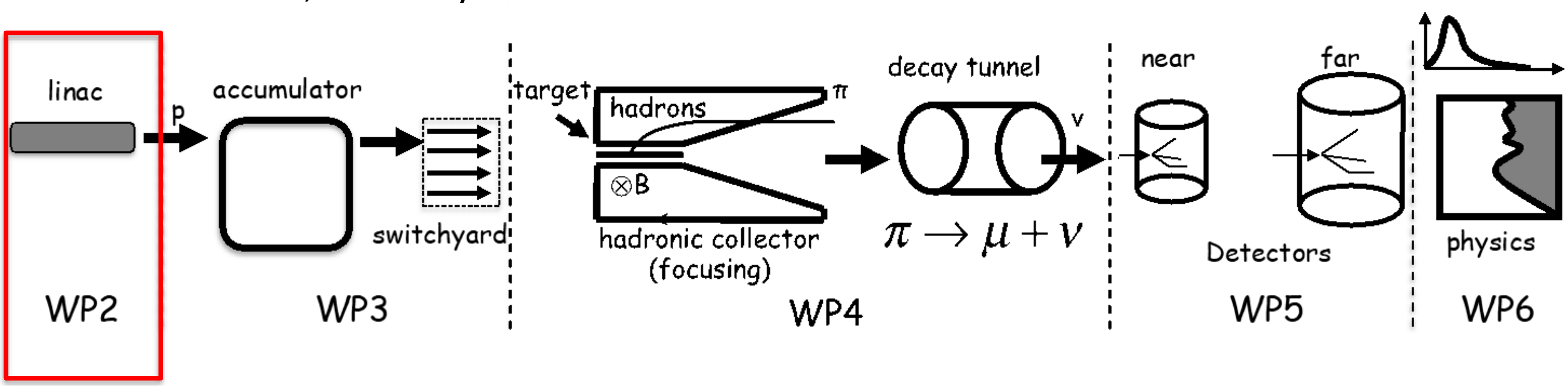
Funded by EU: *Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator*

Marcos Dragos, Status of ESSnuB, Thursday 11:30,

Salvador R. Alcaraz, Thursday

Ye Zou, Thursday

Marcos Dragos, Monday



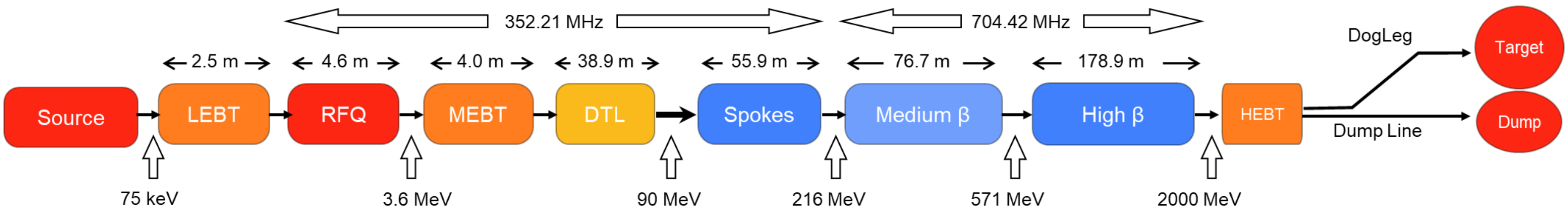
From Marcos Dragos talk, Monday

ESSnuSB upgrade options

- The ESSnuSB requires the ESS linac to provide an additional 5 MW of beam power for neutrino generation.
- Any energy upgrade beyond 2 GeV will simplify the delivery of a second 5 MW beam from the ESS linac, lower current.
    - With the energy upgrade to **2.5 GeV** the increase of average power needed from the nominal Radio Frequency (RF) stations is **~60%,** which looks feasible within the existing RF gallery space.
    - An energy upgrade to 3 GeV would further decrease the need for higher RF power from the existing stations to ~30%.

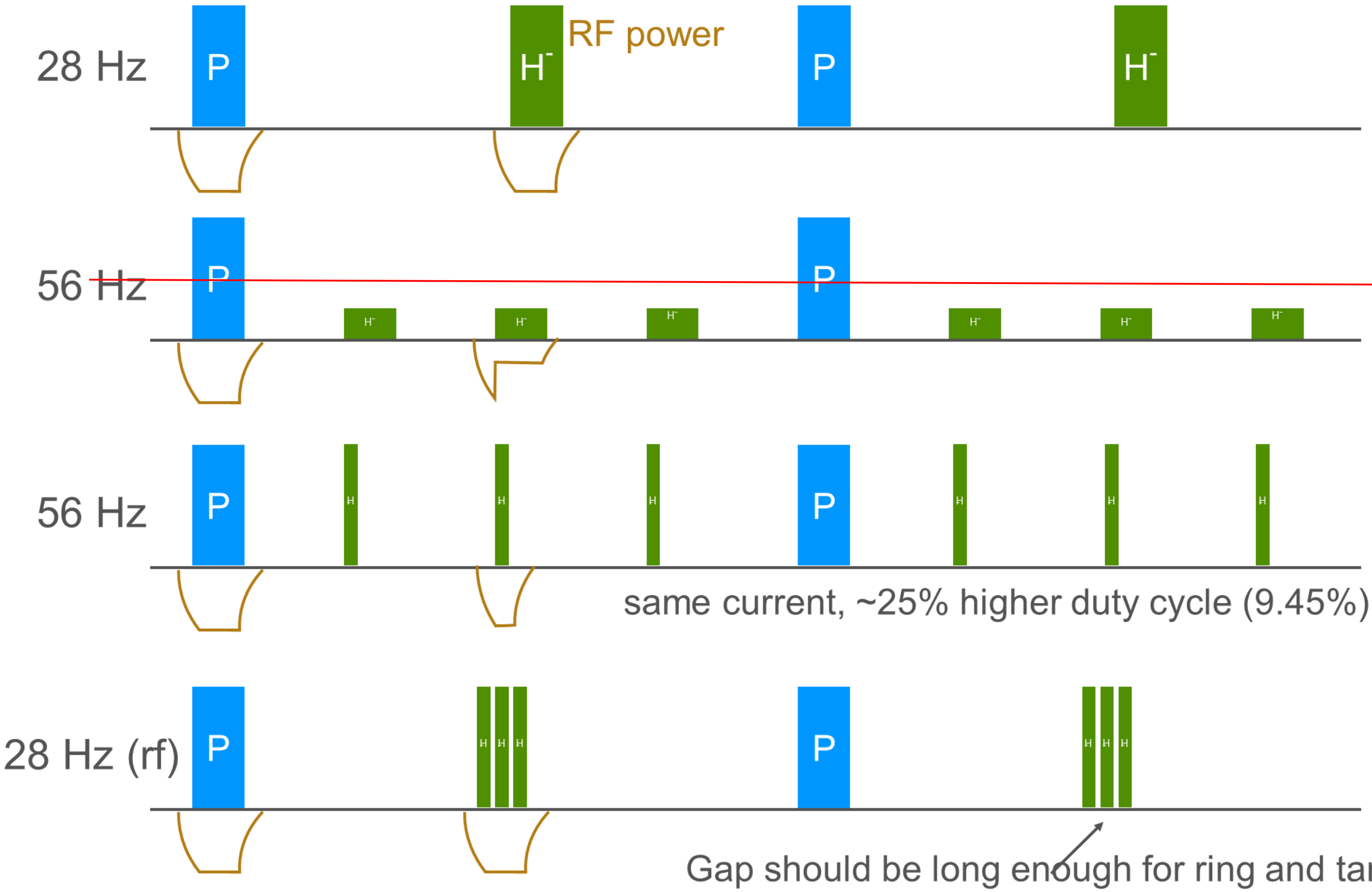
Extracted from the assessment report by Frank Gerigk and Eric Montesinos, CERN-ACC-NOTE-2016-0050

Accelerator – upgrade



Parameter	Value	Upgrade (n+ν)	Upgrade (n+ν)
Ion species	Proton	Proton + H^-	Proton + H^-
Average beam power	5 MW	10 MW	10 MW
Ion kinetic energy	2 GeV	2 GeV	2.5 GeV
Average macro pulse current	62.5 mA	62.5 mA	50 mA
Average macro pulse length	2.86 ms	>2.86/4 ms	> 2.86/4 ms
Pulse repetition rate	14 Hz	$\geq$ 28 Hz	$\geq$ 28 Hz
Duty cycle	4%	$\geq$ 8%	$\geq$ 8%
Maximum accelerating cavity surface field	45 MV/m	45 MV/m	45 MV/m
Linac length	352.5 m	352.5 m	352.5 + ca 70 m

Pulsing schemes



8 % duty cycle

Not compatible with present RF modulator design.

Gap should be long enough for ring and target needs, but still much shorter than the filling time of cavities

Low energy section

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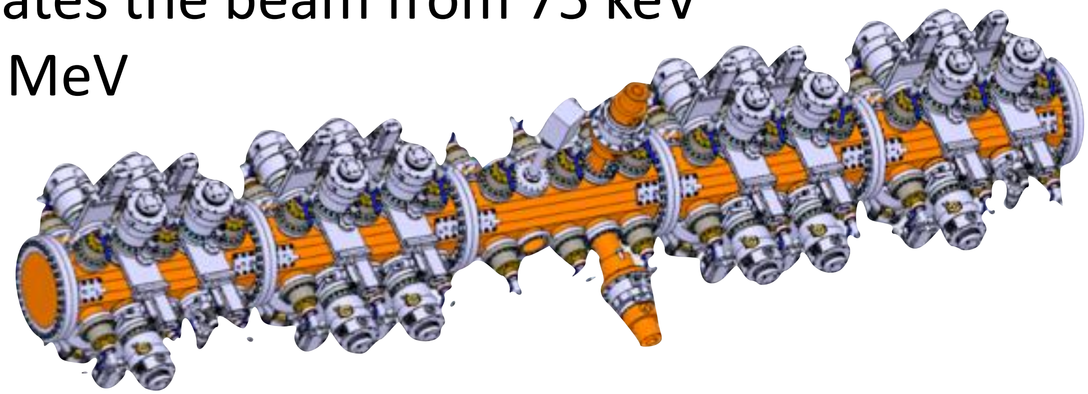
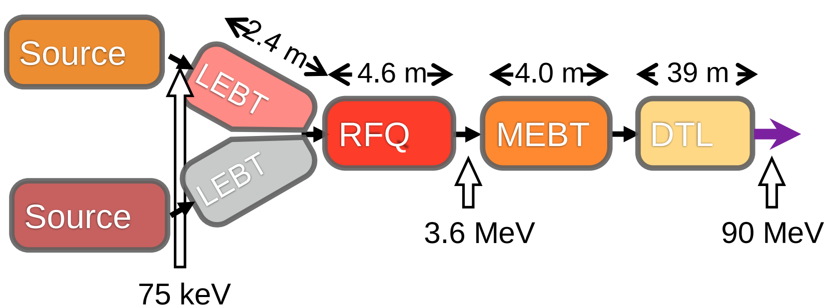
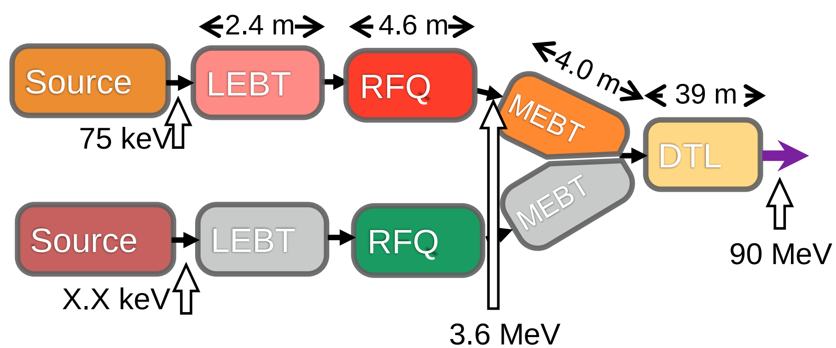
- Accelerates the beam from 75 keV to 3.62 MeV





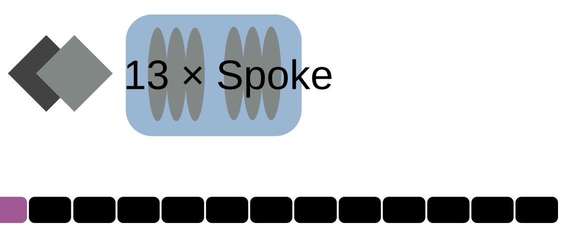


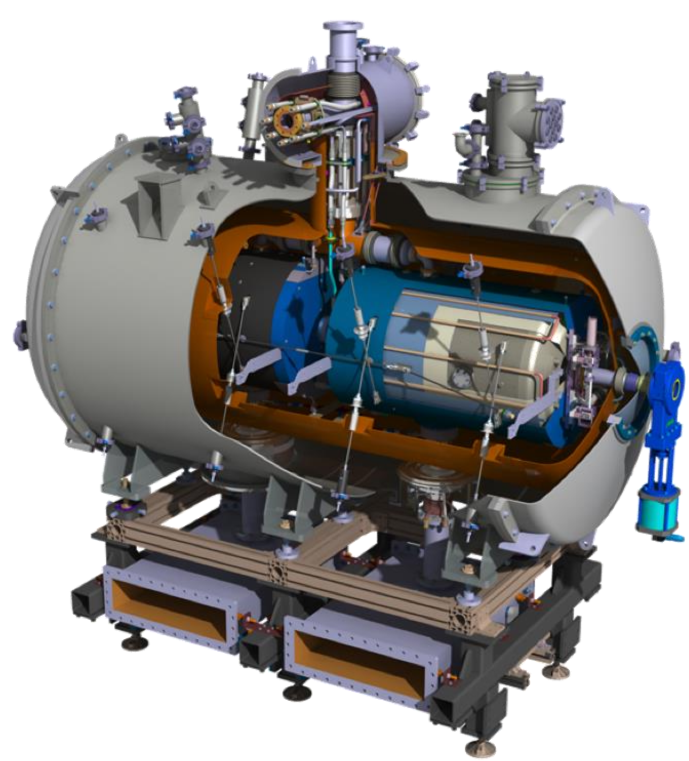
RFQ and DTL

- The DTL is designed (very similar to CERN LINAC4) with a maximum duty cycle of 10%.
- Keeping the (RF) duty cycle below 10% would permit using the same DTL.
- The coupler cooling should be enough for increased duty cycle

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



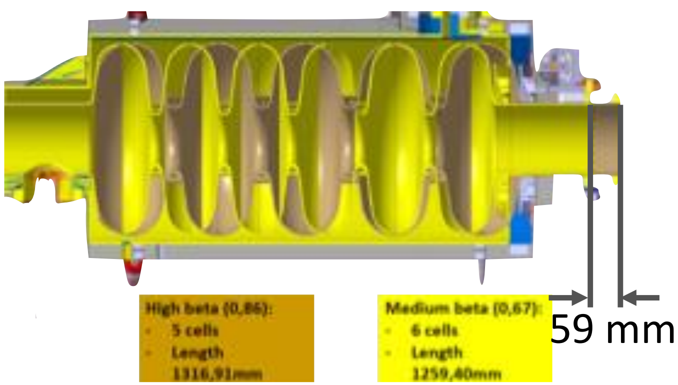


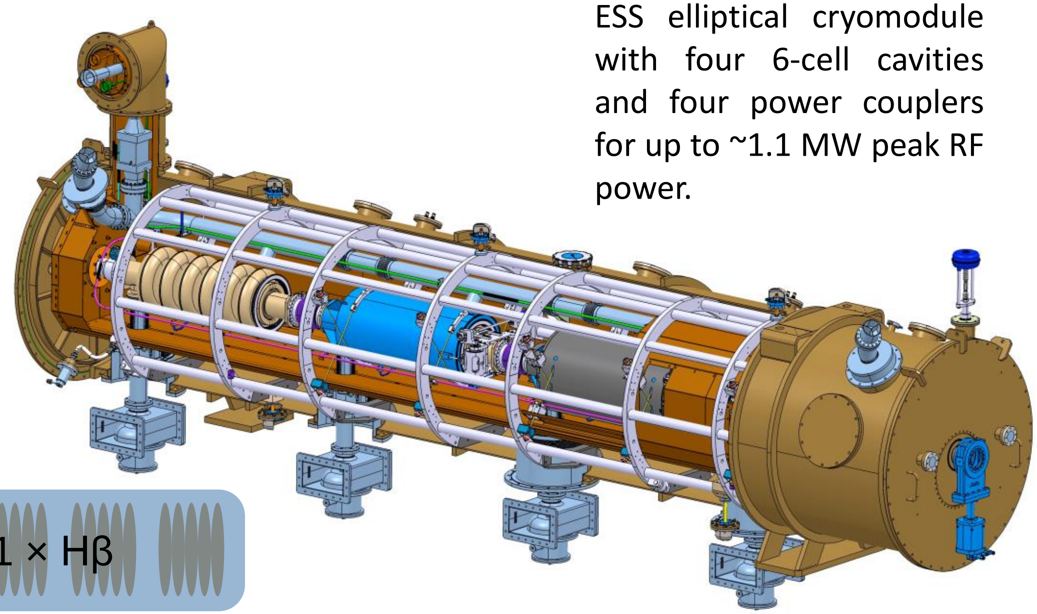
ESS Spoke cryomodule with two double spoke cavities, and two power couplers

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

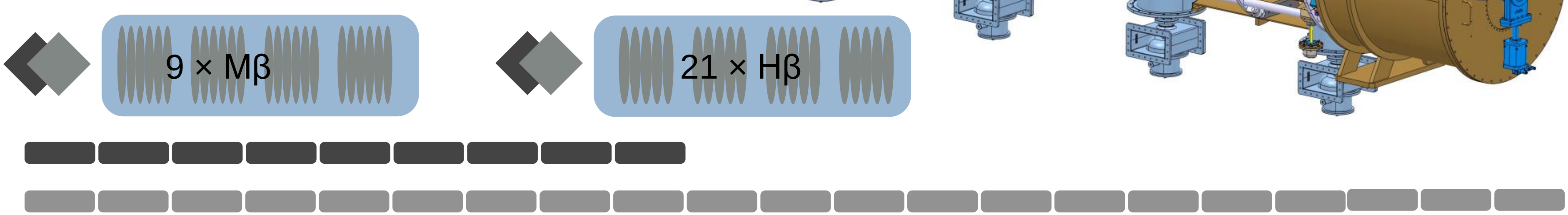
  6-cell, $\beta g = 0.67$, $E_{acc} = 16.7$ MV/m

  5-cell, $\beta g = 0.86$, $E_{acc} = 19.9$ MV/m

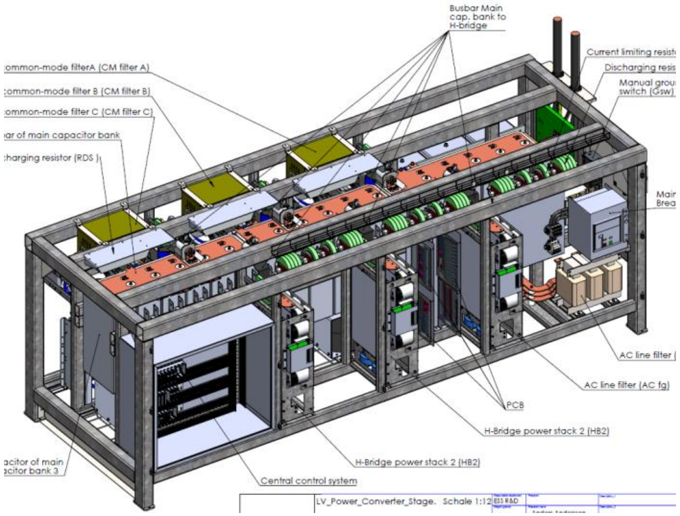




ESS elliptical cryomodule with four 6-cell cavities and four power couplers for up to ~1.1 MW peak RF power.



Modulator



- The ESS modular topology of modulators would permit increasing the output power by increasing the size of capacitor charger.
- If each modulator is feeding 4 klystrons (660 kVA case), there should be enough space saved to add the extra capacitor chargers.
- The life time of the klystrons is reduced to ~half if they run at 28 Hz. Upgrade of klystrons

Thanks to Carlos Martins

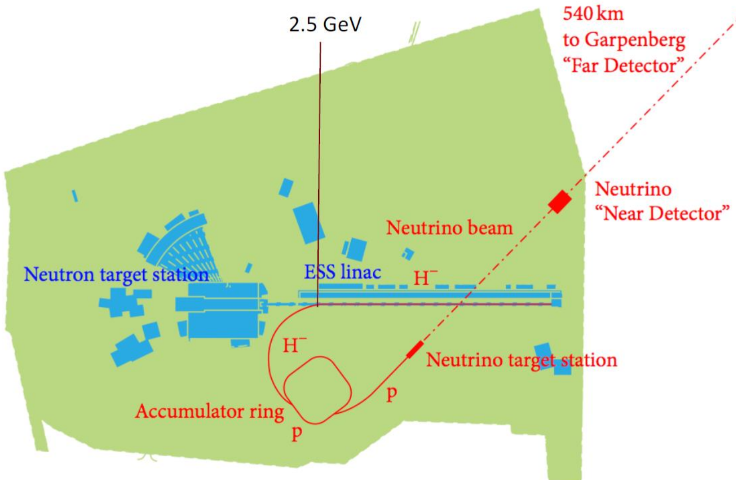
Klystrons

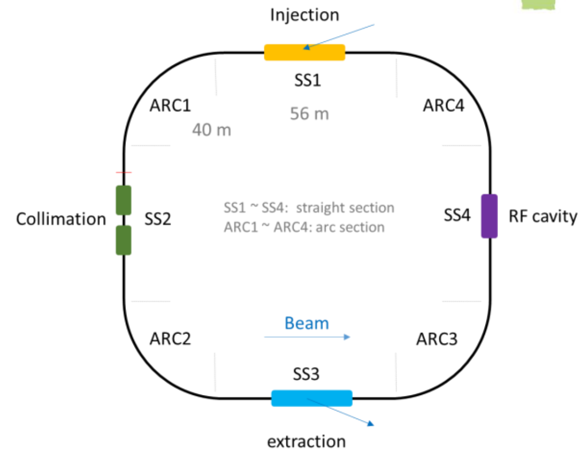
- The current klystrons cannot be operated at four times the average power. (Klystrons could probably be operated at a maximum of 10% RF DC).
  - However, klystrons could be replaced with new different ones at the end of their finite life. This requires early knowledge of such a need.
- The utilities such as water cooling should be increased.
  - To remove the excess heat one can alter the flow rates by changing the pipe sizes or increased pressure.
  - One can also increase the temperature gradient.
- Increasing the number of klystrons does not seem feasible due to space and utility restrictions

Extraction gap for accumulator ring

EUROPEAN SPALLATION SOURCE

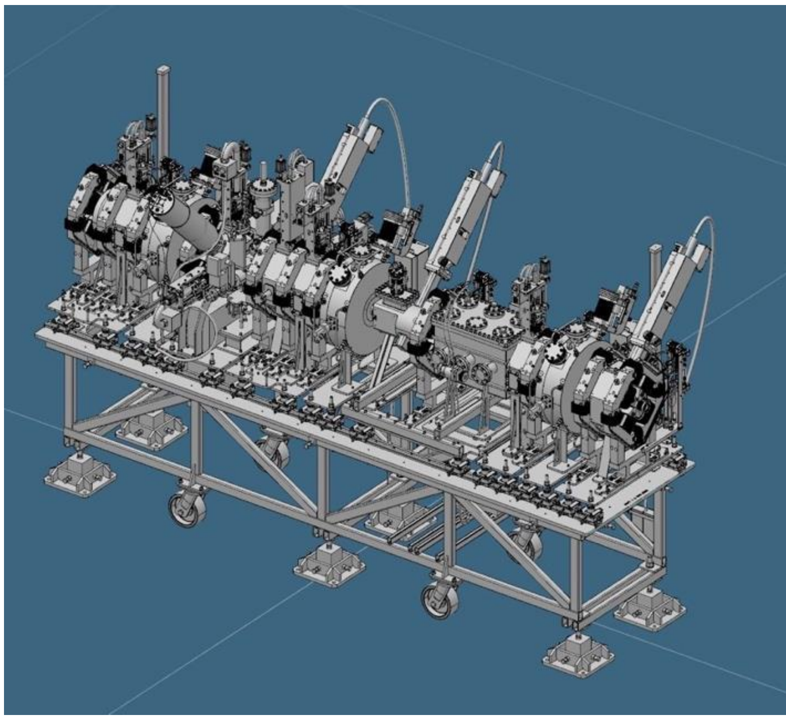
- An extraction gap is needed not to lose beam while extracting from the accumulator ring.
- The extraction gap is created in the linac and preserved when stacking beam in the accumulator ring. The gap will be created by the chopper in the MEBT.
- The chopper is designed for a rise and fall time of < 10 ns.

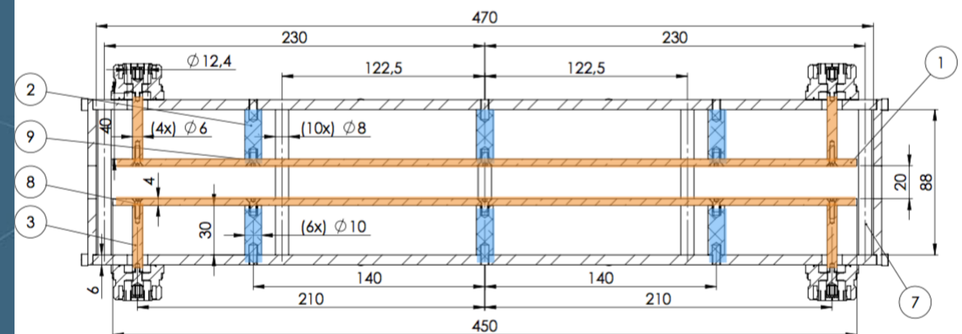




Accumulator ring layout (Ye Zou, Thursday)

MEBT Chopper



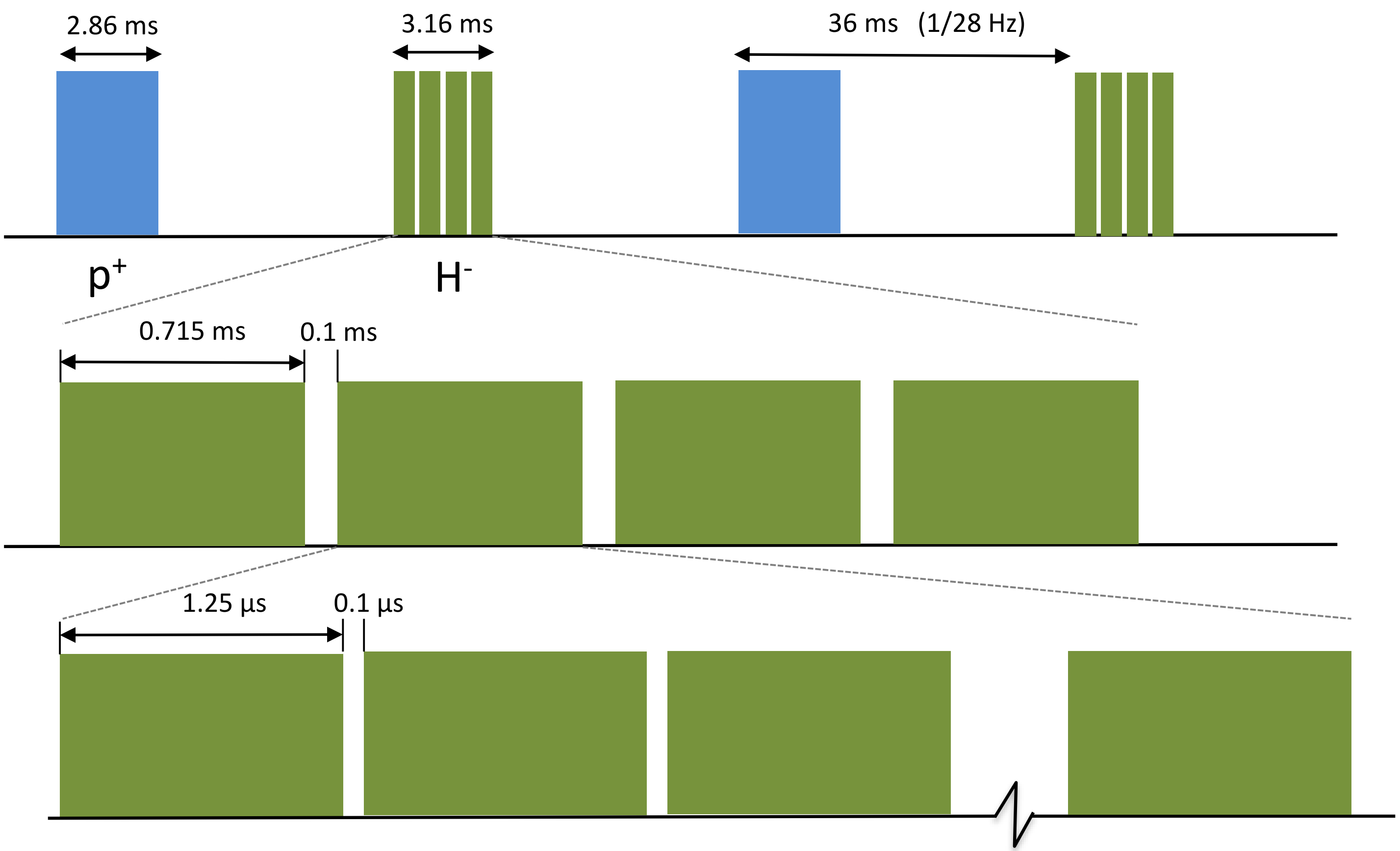


MEBT chopper will be used to create the gaps

Pulse structure

Each pulse $1.1 \cdot 10^{15}$ particles

28 Hz (RF)



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

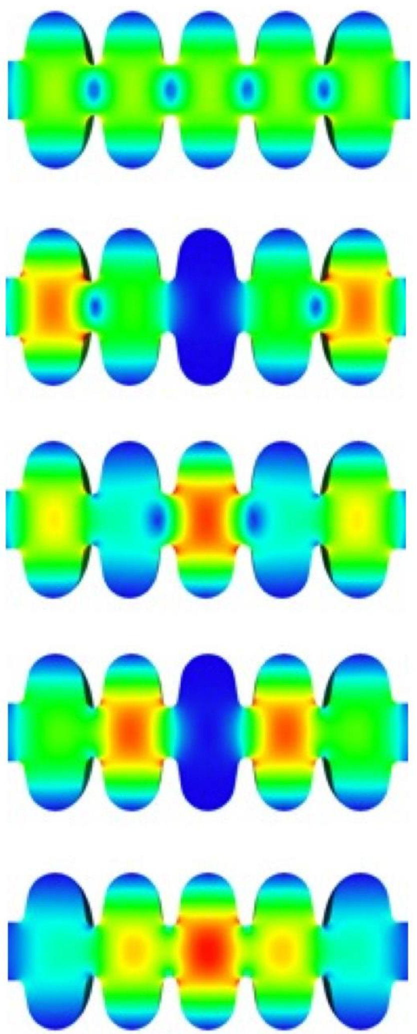
Chopped subpulse with extraction gap 100 ns (extraction kicker rise time)

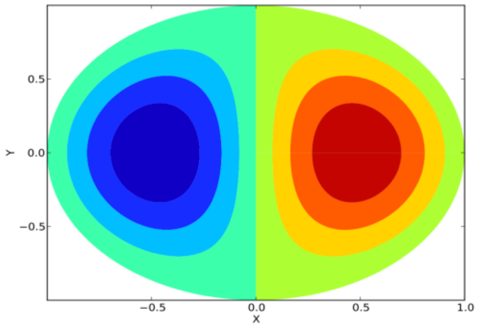
530 pulses with $5.2 \cdot 10^{11}$ particles.
In total $2.75 \cdot 10^{14}$ per ring filling.

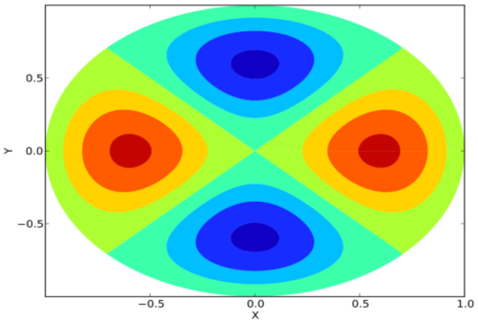
Micro bunches, 2.84 ns (352 MHz)

Higher / Same Order Modes

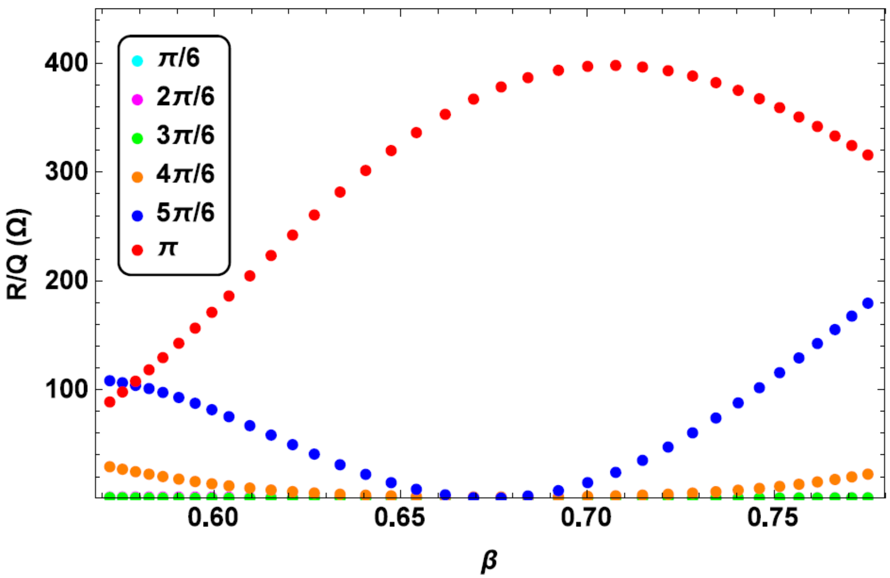
- Creating an extraction gap in the ring requires a high frequency chopping in the linac, which could excite HOMs / SOMs in the SC cavities.
- SOMs can cause cavity heating, leading to higher cryogenic load, and affect the beam dynamics. (ESS design does not include HOM couplers.)
- A study of the effects of the SOMs has to be carried out.
- Alternatively create the extraction in the accumulator ring. But not trivial. (See talk by Ye Zou)

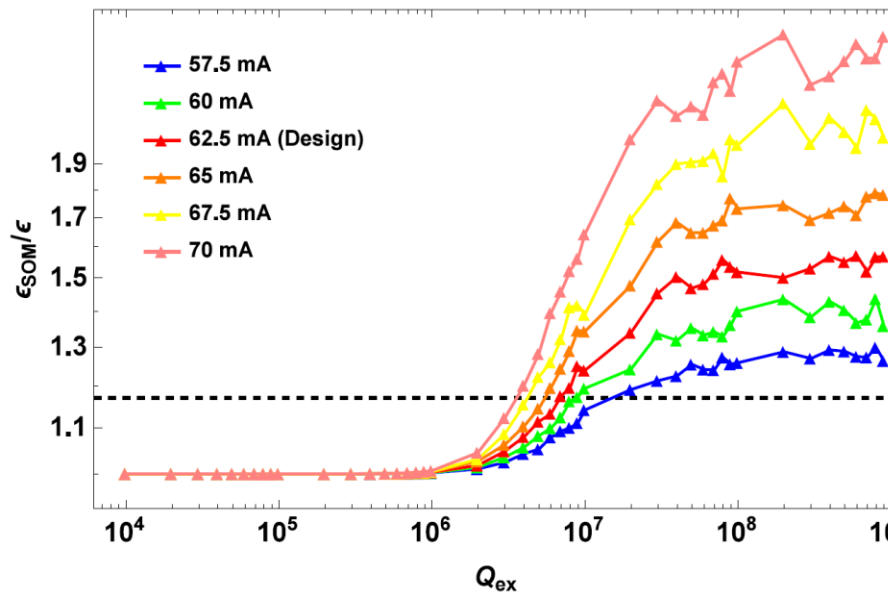






- Simulation of SOMs in ESS linac in standard mode, without extraction gap.





Medium β section, R/Q (proportional to V_{acc}^2), for different SOMs

5π/6 mode can cause problems in the beginning of medium β section

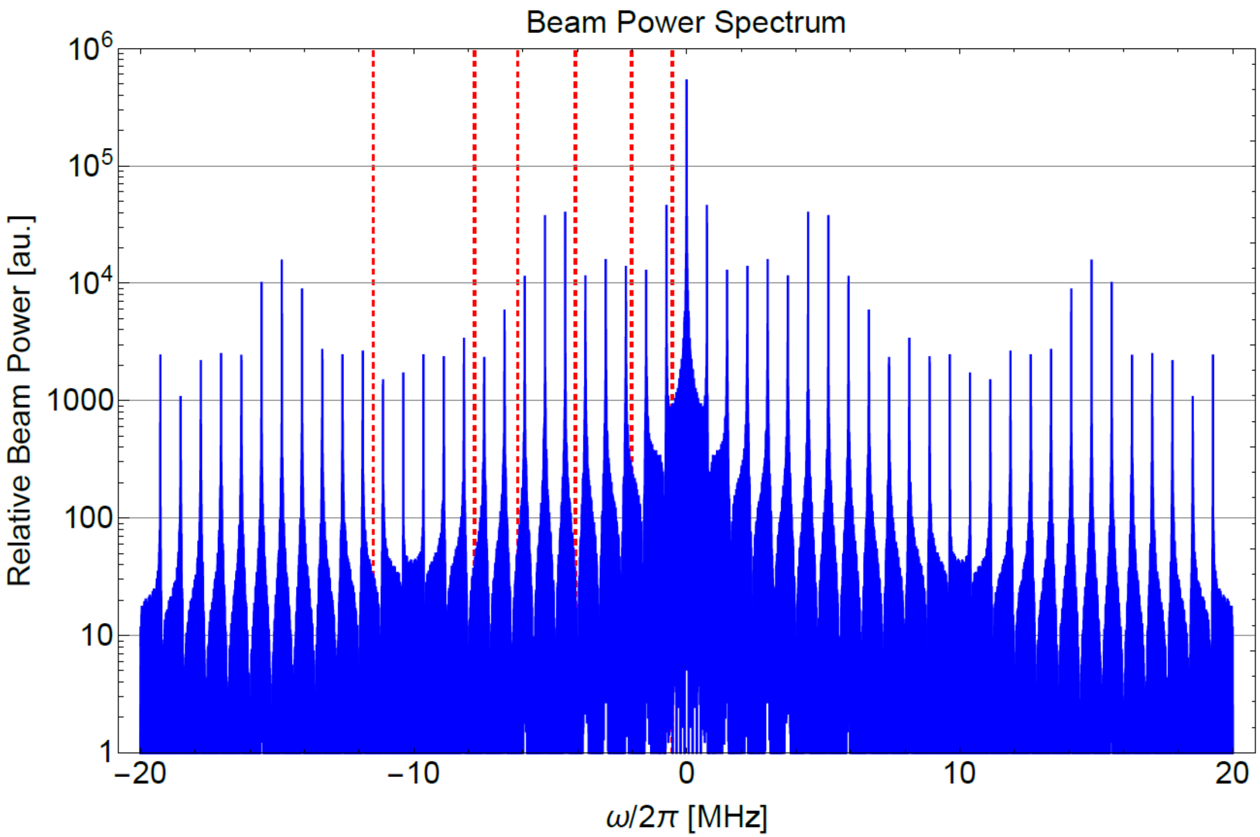
The total emittance growth in ESS linac observed due to longitudinal SOMs. Qs of ESS cavities ~10^5

Small effect on the total emittance

Aaron Farricker, Thesis, Manchester Univ. 2017

Same Order Modes – simulations

- **Preliminary** results from simulations of SOM effects in medium beta cavities. **With** an extraction gap in the pulse structure.



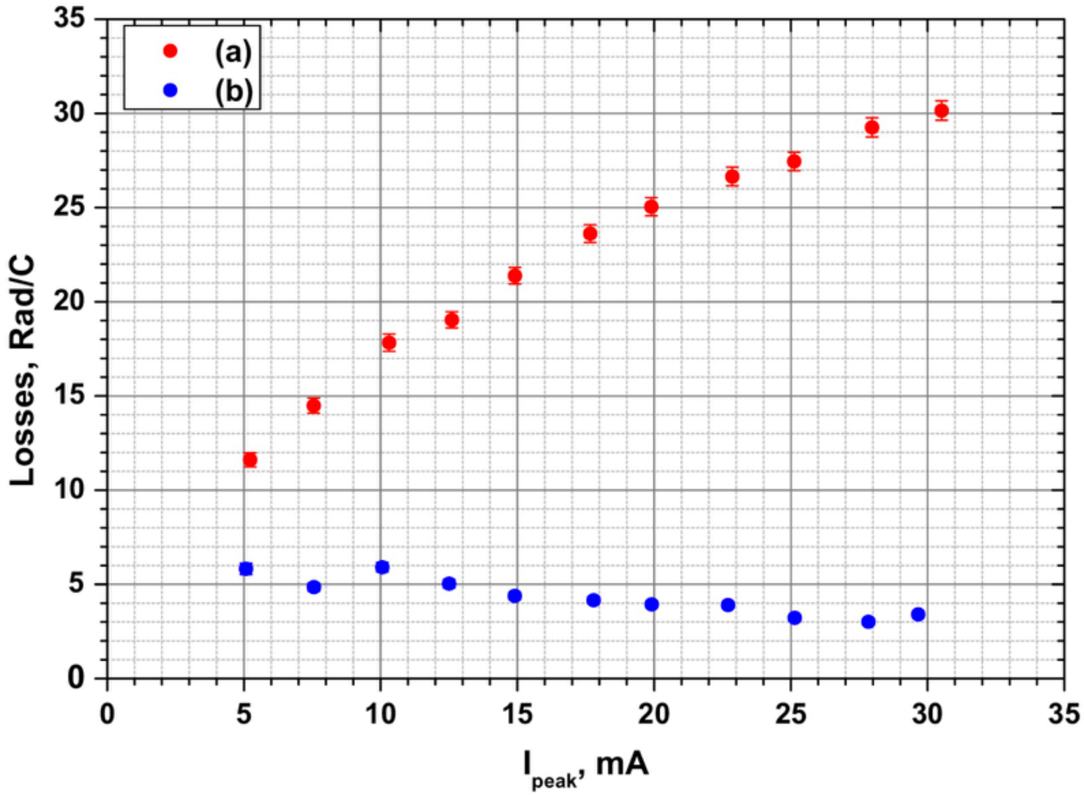
Preliminary results show that the closest side band is damped by a factor of 20. 5π/6 closest passband.

To be continued…

By Aaron Farricker, CERN

P Losses and H⁻ intrabeam stripping

Shishlo et al, PRL 108, 114801 (2012)

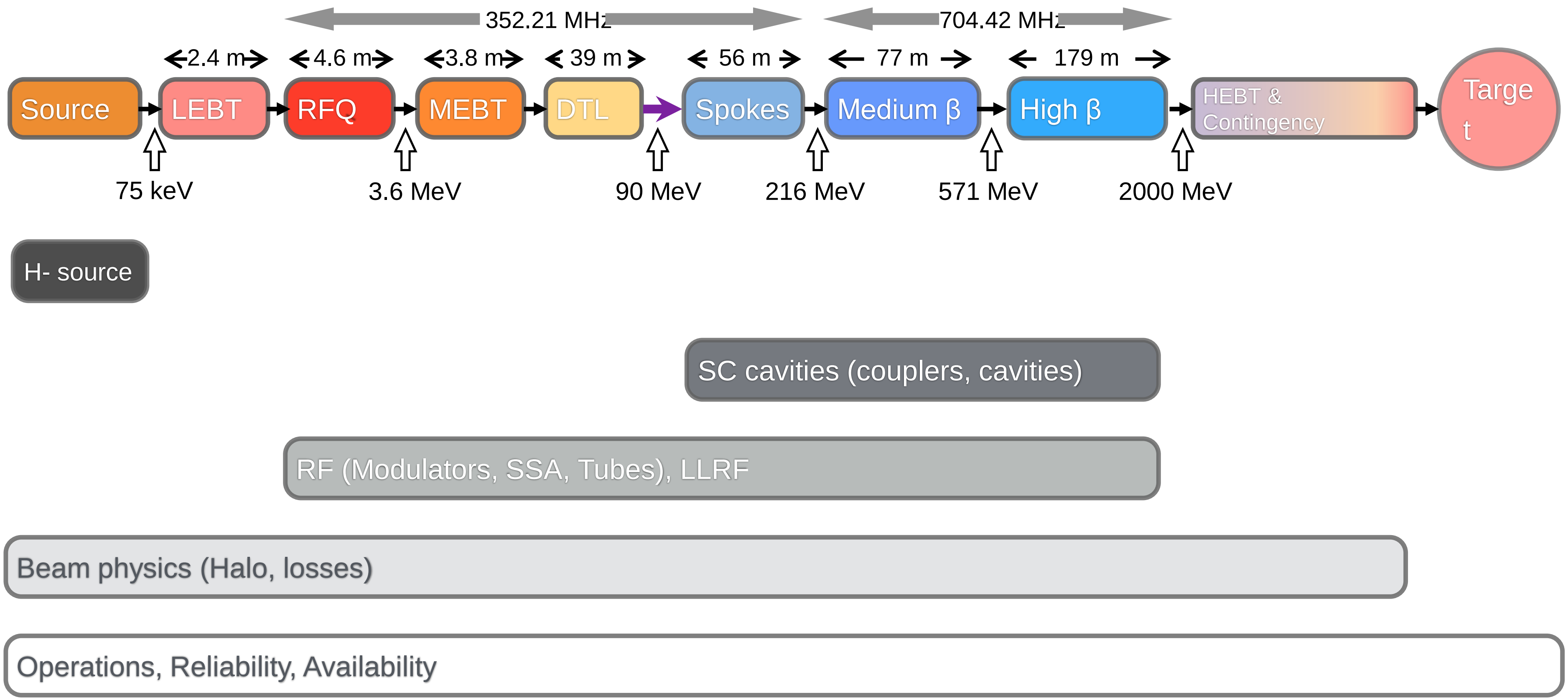


Problems with beam losses in SNS due to H^- intrabeam stripping.

Needs attention in ESSnuSB

Normalised beam loss (BLMs) vs beam current for P (blue) and H^- (red)

ESSnuSB



352.21 MHz
704.42 MHz
2.4 m
4.6 m
3.8 m
39 m
56 m
77 m
179 m
Source
LEBT
RFQ
MEBT
DTL
Spokes
Medium β
High β
HEBT & Contingency
Target
75 keV
3.6 MeV
90 MeV
216 MeV
571 MeV
2000 MeV
H- source
SC cavities (couplers, cavities)
RF (Modulators, SSA, Tubes), LLRF
Beam physics (Halo, losses)
Operations, Reliability, Availability

Summary

- The identified major modifications for the doubling of the beam power via a higher repetition rate and higher beam energy are (in no particular order):
  - Three new electrical substations along the RF gallery.
  - A third main electrical station, alongside the 2 existing ones.
  - HV cable trenches and pulling of additional HV cables from the main station towards the new substations. New HV cables between the substations and the modulators in the RF gallery.
  - Installation of 8 new cryo modules and associated RF stations.
  - Change of klystron collectors, so that 60% more average power can be produced. If klystrons are at the end of their lifetime, they could be exchanged against more powerful models.
  - Installation of additional capacitor chargers to allow faster pulsing of the modulators. This is only possible if the modular design developed in-house is adopted.
  - Installation of a H- source + RFQ + MEBT + beam funnel alongside the existing protons source.
  - Exchange trim magnets and associated power supplies against pulsed versions
- The reviewers, Frank and Eric, did not find any show stoppers for the addition of 5 MW H- acceleration capability in the current state of the ESS linac.

Extracted from the report by Frank Gerigk and Eric Montesinos, CERN-ACC-NOTE-2016-0050

Summary cont'd

- Beam losses due to H- intrabeam stripping needs to be considered (SNS).
- The effects of SOMs due to extraction gap in the beam pulse needs to be further studied.
- If the SOMs cause severe problems, consider different pulsing schemes, create gap in accumulator ring (not trivial).

Acknowledgements

Thanks to

- Mamad Eshraqi, ESS
- Aaron Farricker, CERN, Simulations HOM/SOM
- Marcos Dragos, Tord Ekelöf, Maja Olvegård, Ye Zou, Elena Wildner, Roger Ruber