

### On behalf of many ESS stuffs and collaborators...



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#### STATUS OF THE NORMAL CONDUCTING LINAC AT THE **EUROPEAN SPALLATION SOURCE**

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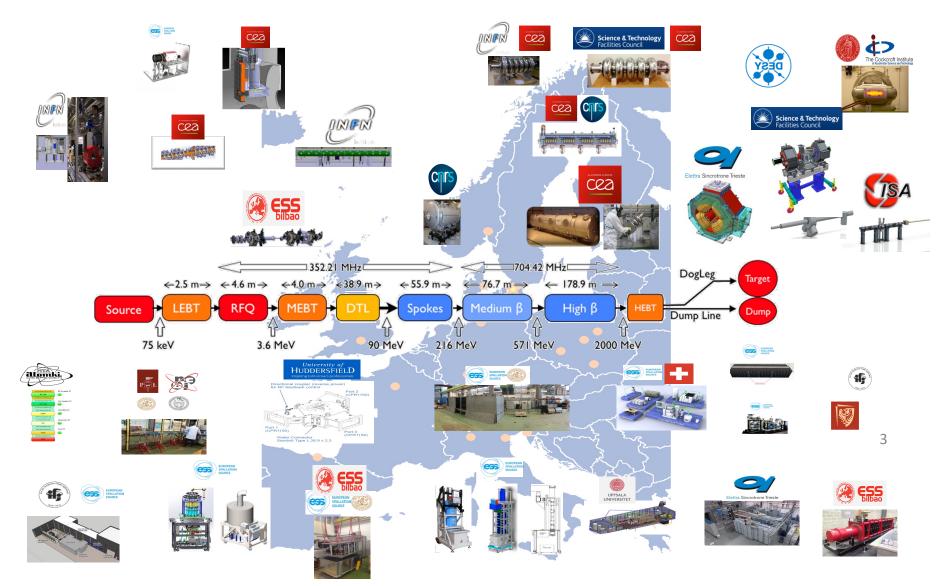
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# ESS linac project as European collaboration





#### Outline



- ESS linac and commissioning
- Recent project highlights (slide-show)
- Normal-conducting (NC) linac sections
- NC linac commissioning highlights
  - Major points of NC linac commissioning



# **ESS Linac and Commissioning**

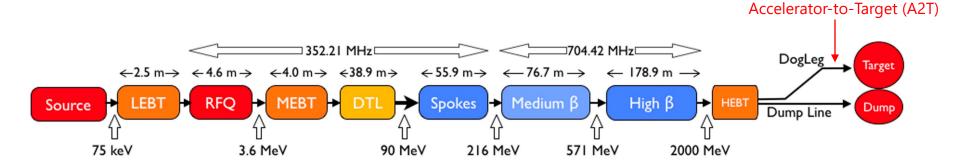
# Single page summary on ESS project and linac



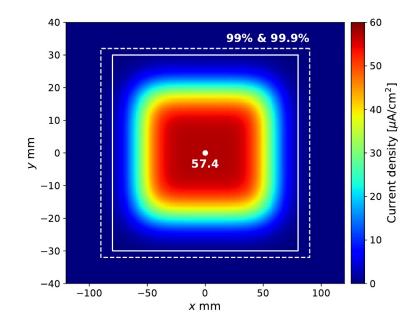
- European Spallaton Source (ESS) is ...
  - Under construction in Lund, Sweden.
  - User program from 2025.
  - Driven by a high-power proton linac.
    - Normal-conducting (NC) linac + superconducting (SC) linac.
    - No accumulator ring.
    - Design: 2 GeV and 5 MW
    - Initial operations (with limited RF sources): 800 MeV and 2 MW
  - Upgrade study ongoing for neutrino program
    - Upgrade to 10 MW.
    - Proton and H- in parallel.
    - Accumulator ring.
- NC linac
  - Full current beam (62.5 mA) through DTL tank 1 (out of 5).
    - Commissioning done with missing systems/functinalities so far from completed.
  - Commissioning to DTL tank 4 next year.
- SC linac
  - Installations and testing in the tunnel and garally progressing (RF, cryo, controls, ...)
  - Manufacturing and testing of superconducing cavities and cryomodules ongoing.

# ESS proton linac overview: high level parameters





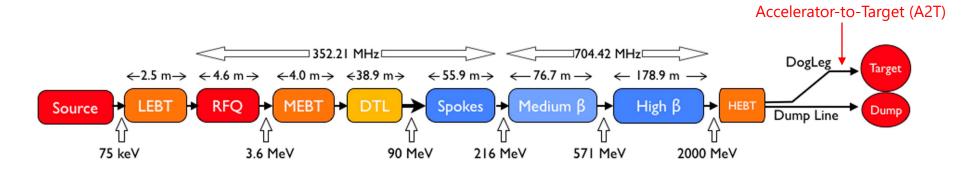
Parameter	Value
Ave power (design) [MW]	5
Max energy (design) [MeV]	2000
Ave power (initial) [MW]	2
Max energy (design) [MeV]	800
Peak current [mA]	62.5
Pulse length [ms]	2.86
Rep rate [Hz]	14
Duty cycle [%]	4
RF freq [MHz]	352.21/704.42



Beam footprint on target by raster system in A2T

# ESS proton linac overview: lattice parameters





	Length	No. Magnet	#Cav  imes etag/(Opt)	No. Sections	Power (kW)	IK partner
LEBT (from Plasma)	2.7	2 Solenoids	_	I		INFN-LNS
RFQ	4.5	_	T	I	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	$26 \times (0.50)$	13	330	IPNO
Medium Beta	76.7	18 Quads	36 × 0.67	9	870	LASA / CEA
High Beta I (~1.3 GeV)	93.7	22 Quads	44 × 0.86	11	1100	STFC / CEA
High Beta II	85.2	20 Quads	40 × 0.86	10	1100	STFC / CEA
Contingency + HEDP	132.3	32 Quads	_	15	_	Elettra
DogLeg	64.4	12 Quads + 2	_	I	_	Elettra
A2T	44.7	6 Quads + 8 Raster	_	I		Aarhus Uni
	603.0					

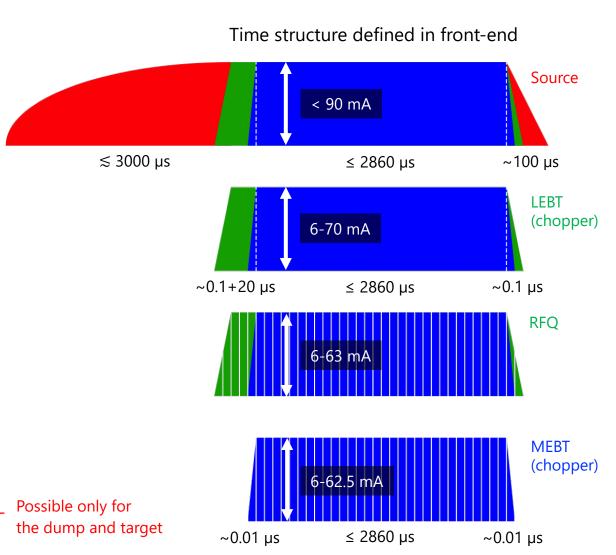
### Beam pulse time structure



#### Beam (envelope) modes

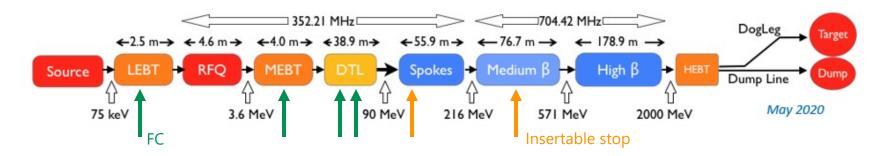
- Tied to beam permit and machine protection
- Requirements for stops and diagnostics

Mode	Current [mA]	Length [µs]	Rep [Hz]
Probe	≤ 6	≤ 5	≤ 1
Fast commissioning	≤ 6	≤ 5	≤ 14
RF test	≤ 6	≤ 50	≤ 1
Stability test	≤ 6	≤ 50	≤ 14
Slow commissioning	≤ 62.5	≤ 5	≤ 1
Fast tuning	≤ 62.5	≤ 5	≤ 14
Slow tuning	≤ 62.5	≤ 50	≤ 1
Long pulse verification	≤ 62.5	≤ 2860	≤ 1/30
Production	≤ 62.5	2860	14



# Beam stops and diagnostics





Device	Туре	IS	LEBT	RFQ	MEBT	DTL	SPK	MBL	HBL	HEBT	A2T	DmpL	Total
Faraday cup	Current		1		1	2							4
BCM		1	1	1	2	5		1	1	2	3	2	19
Fast BCM					2								2
Doppler			1										1
BPM	Parasitic				7	15	14	9	21	16	12	4	98
Non-invasive profile	transverse		2		2		1	3	1		1		10
Imaging	Parasitic										2	1	3
Grid	target/dump transverse										1		1
Aperture											3	1	4
Emittance	Non-parasitic		1		1								2
Bunch shape					1		1						2
WS					3		3	3	1	3	1		14
BLM	Loss				4	47	78	38	86	51	38	6	348

### Commissioning strategy and where we are

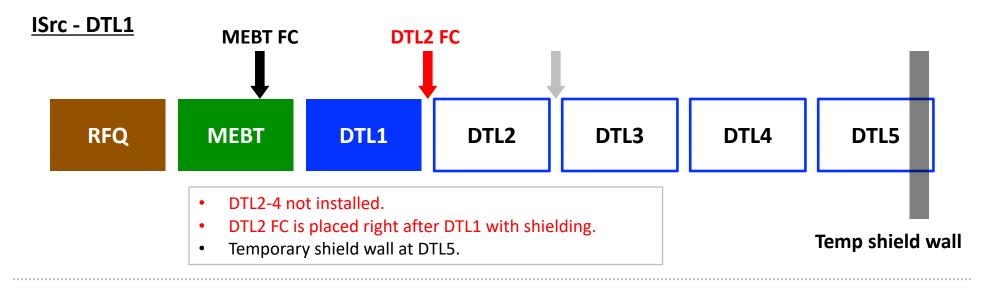


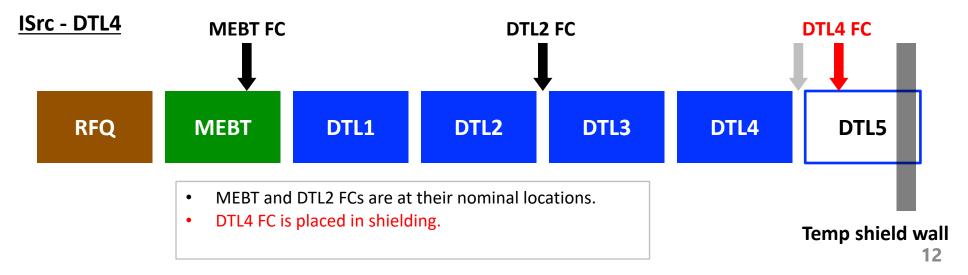
Final Destination	Start (Current)	End (Current)	Start (2018 Baseline)	Start (Original)
LEBT	2018-09-19	2019-07-03	2018-06-28	2017-11-20
MEBT	2021-11-10 2022-02-23 2022-04-06	2021-12-17 2022-03-12 2022-05-23	2019-11-04	2018-11-05
DTL1	2022-05-30	2022-07-13		
DTL4	2023-03-08	2023-06-19	2020-04-27	2019-01-24
Dump	2024-07-15 (570 MeV)	2024-10-15	2021-02-08 (570 MeV)	2019-05-13 (2 GeV)
Target	2025-04-24 (570 MeV)		2022-06-08 (1370 MeV)	2019-06-24 (2 GeV)

- No temporary stop nor diagnostics after the first step for the source+LEBT. At least we kept reasonable set of permanent diagnostics throughout the linac.
  - So that we can repeat any missed/failed test later.
- Aggressive schedule means that the driver of commissioning plan is the situations of installation, integration to control system, and hardware testing.
  - The focus of commissioning is to make all systems work and establish the minimal beam to the final destination, instead of fully characterizing high current beam.
  - We didn't have schedule and resource for deploying a test bench, anyway.
- This strategy of deprioritizing high current beam aligns to the user's demands on 2.86 ms and 14 Hz.

# NC linac commissioning configuration (updated)









Recent Project Highlights (Slide-show)

# IS, LEBT, RFQ, and MEBT (without cables)





# IS, LEBT, RFQ, and MEBT (with cables)







# DTL tank 1





# RF systems





Operational for NC linac





# Cryomodule assembly ongoing at in-kind





Elliptical cryomodules at CEA

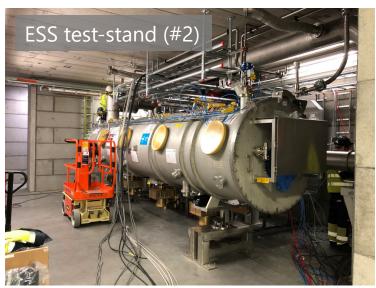


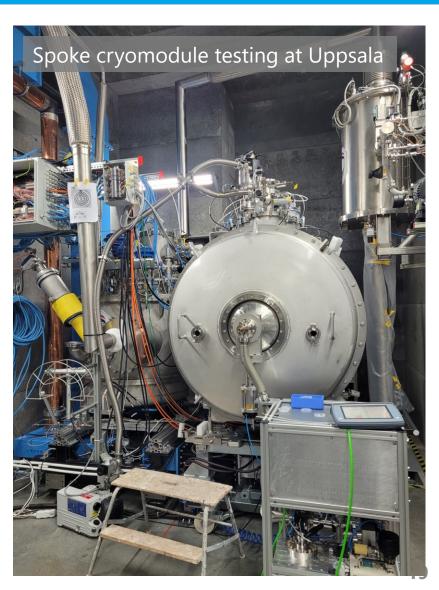
Spoke cryomodules at IJC-Lab

# SC cavities and cryomodule testing ongoing









# Cryomodules delivered to the ESS site



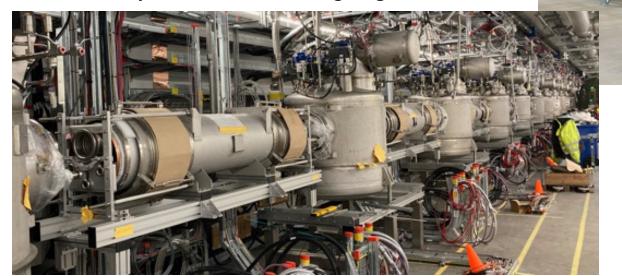




# Cryo system



Distribution system installation ongoing



Test ongoing for years

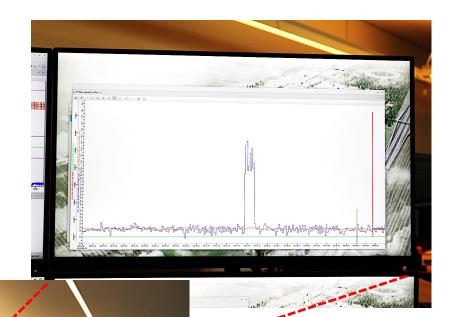
### Very first beam on the ESS site, 2018-09-19



Logbook message ID 69, 2018-09-19 10:31

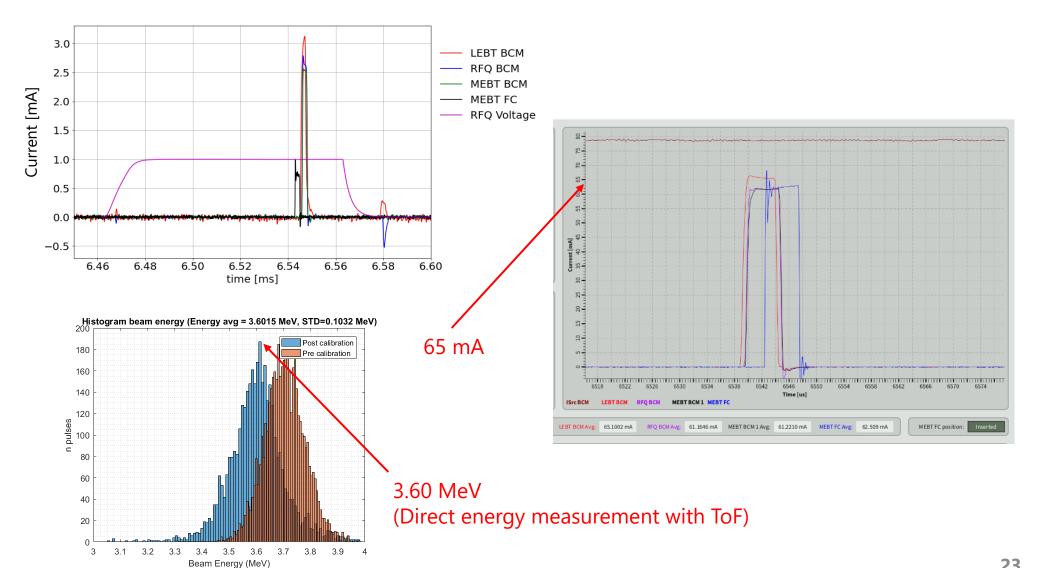
Ryoichi on behalf of ISrc team.

"THE" screenshot of the first beam! Blue trace is the integrated charge per pulse in micro-C. 12 micro-C and 2 ms gives 6 mA. We had the beam for about 10 s.



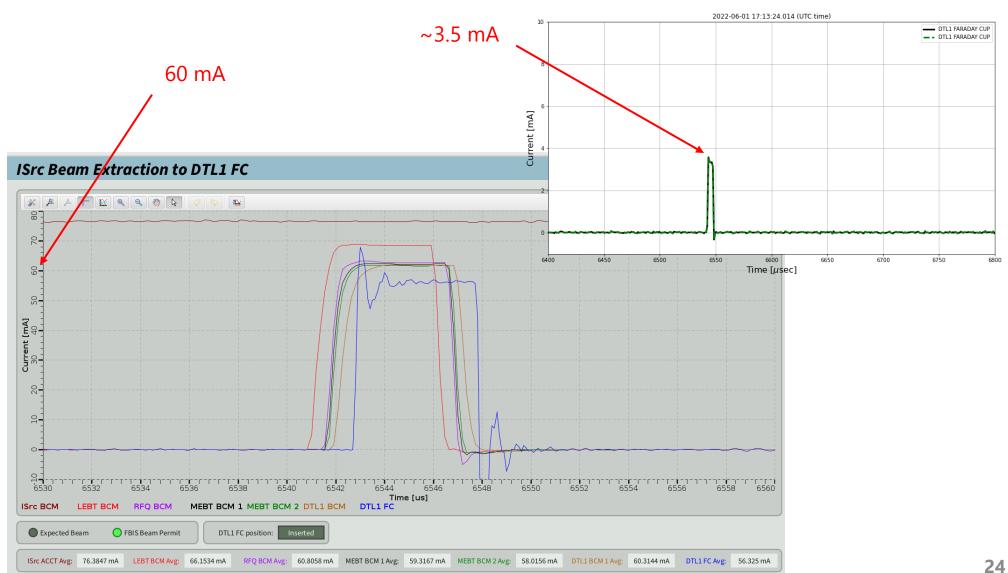
### First beam through RFQ, 2021-11-26 First nominal current beam up to MEBT, 2022-03-12





#### First beam through DTL1, 2022-06-01 First nominal current out of DTL1, 2022-07-01





# End of DTL1 commissioning







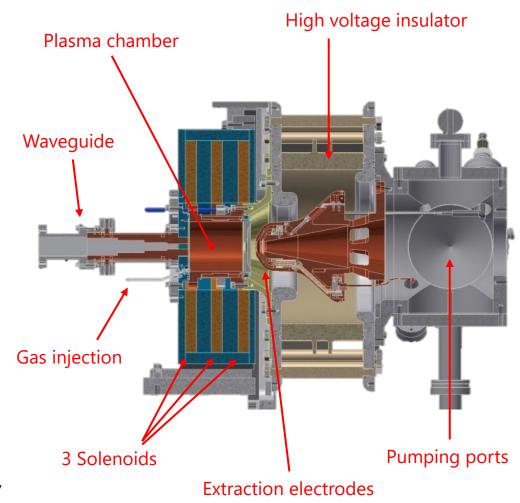
### **NC Linac Sections**

# ESS microwave discharge source



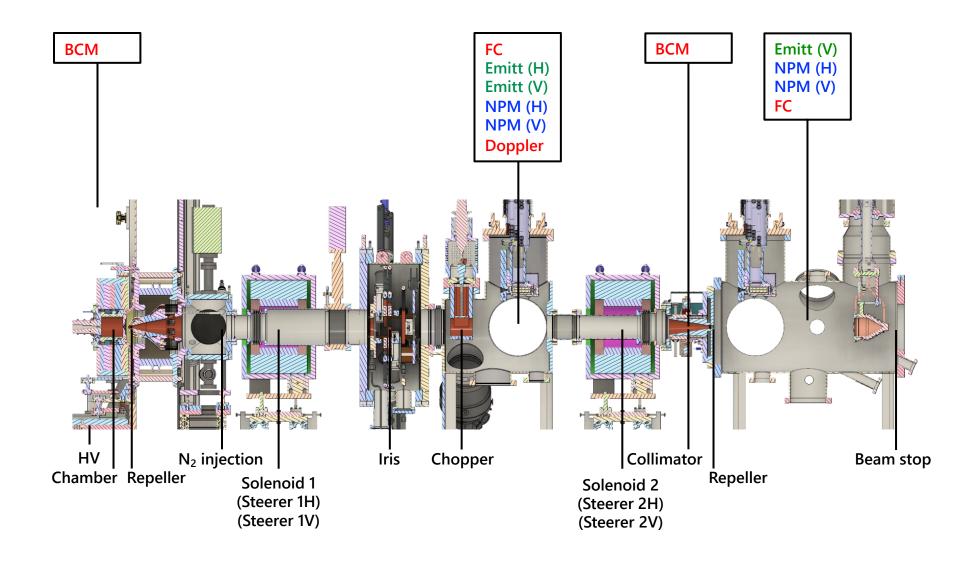
Requirements	Value
Beam energy [keV]	75±5
Proton current [mA]	74
Proton fraction [%]	>75
Pulse length [ms]	6
Pulse flattop length [ms]	3
Rep rate [Hz]	14
Pulse to pulse stability [%]	±3.5%
Pulse flattop stability [%]	±2
Emittance (99%) [π mm mrad]	1.8
Divergence (99%) [mrad]	80

- 5 Primary knobs:
  - RF power
  - H2 flux
  - 3 solenoids (coils) => great flexibility



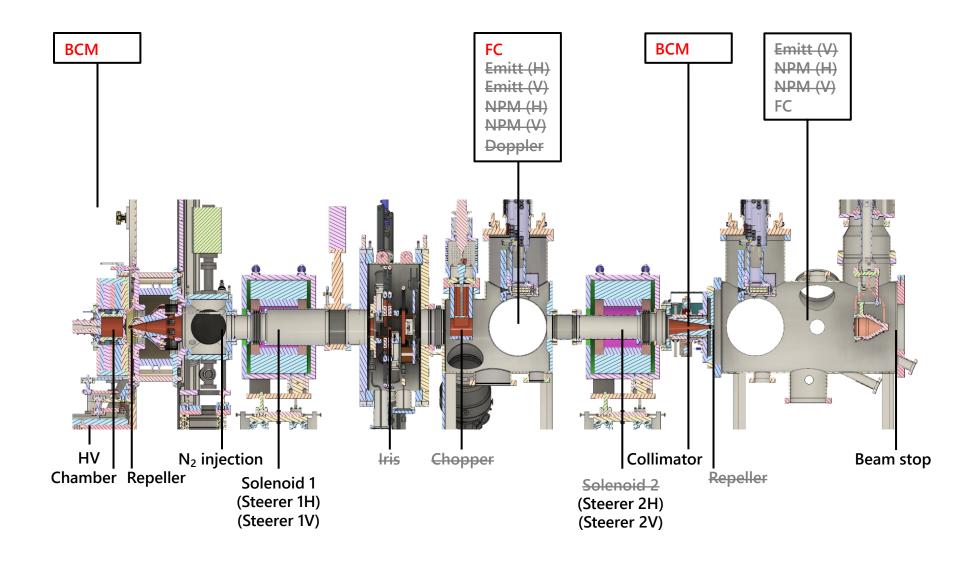
# LEBT systems during beam commissioning





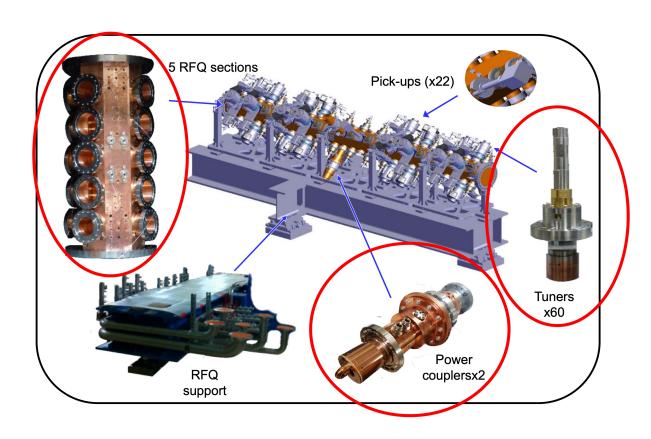
# LEBT systems at the restart





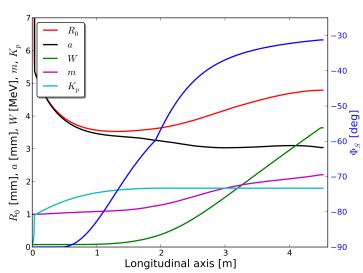
#### **ESS RFQ**





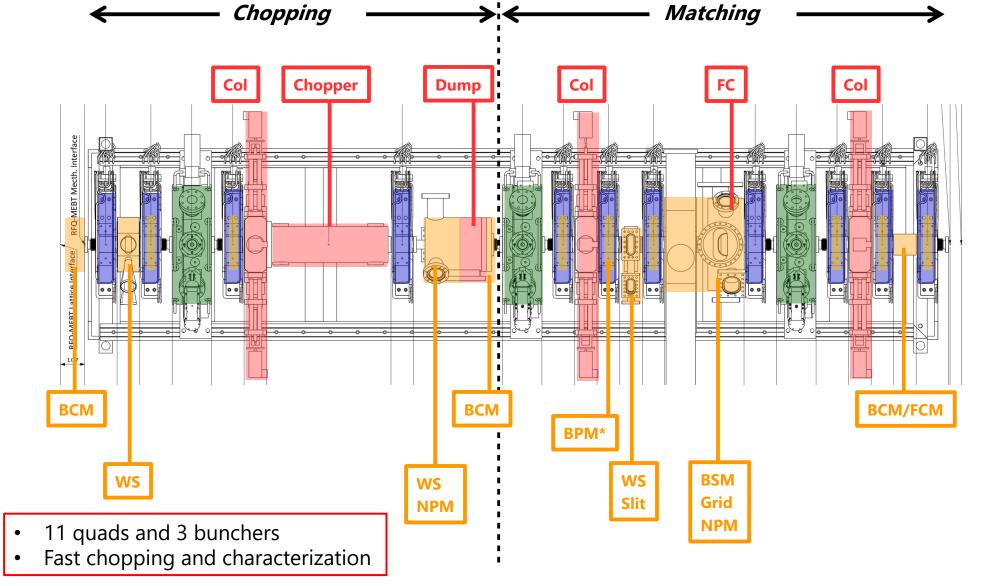
#### The ESS RFQ in numbers

- 4.6 m long
- 2 coaxial power couplers
- 4 vanes ;-)
- 5 segments
- 22 field pickups
- 60 static tuners
- 66 cooling circuits
- 80-120 kV intervane voltage
- 352.21 MHz



#### **ESS MEBT**

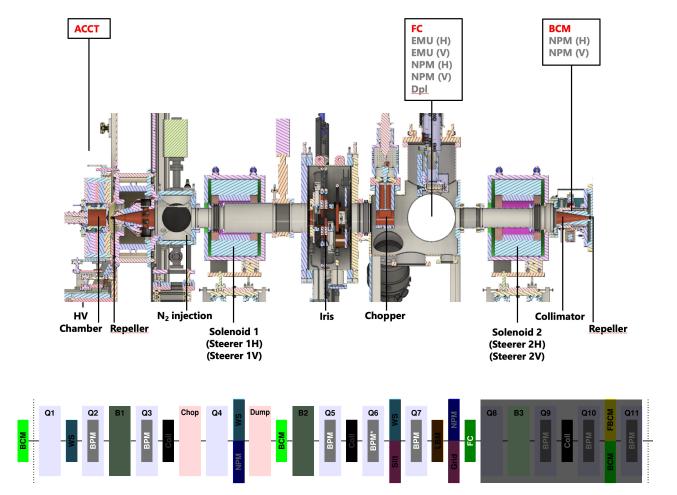




#### Systems status at the start of the MEBT commissioning



- Started with current measurement diagnostics and BPMs.
- Missing Lattice elements
  - MEBT-bunchers
  - MEBT-collimators
- Missing diagnostics
  - LEBT-Dpl
  - LEBT-NPMs
  - LEBT-EMUs
  - MEBT-WSs\*
  - MEBT-NPMs
  - MEBT-EMUs\*
  - MEBT-BSM
- RFQ-LLRF still under testing
  - Feedback\*
  - Feed-forward\*



### ESS DTL1



#### Courtesy of F. Grespan



Tank	1	2	3	4	5
Cells	61	34	29	26	23
E <sub>0</sub> [MV/m]	3.00	3.16	3.07	3.04	3.13
$E_{max}/E_{k}$	1.55	1.55	1.55	1.55	1.55
$\phi_s$ [deg]	-35,-25.5	-25.5	-25.5	-25.5	-25.5
L <sub>Tank</sub> [m]	7.62	7.09	7.58	7.85	7.69
<u>Diam</u> Tank [mm]	521	521	521	521	521
R <sub>Bore</sub> [mm]	10	11	11	12	12
N.PMQ - 1st/last cover	31 - Y/N	18 -Y/Y	15 - N/Y	13 - N/N	12 - Y/N
Radius PMQ [mm]	11	12	12	13	13
L <sub>PMQ</sub> [mm]	50	80	80	80	80
Tun. Range [MHz]	±0.75	±0.75	±0.75	±0.75	±0.75
Q0/1.25	42512	44455	44344	43894	43415
Optimum β	2.01	2.03	2.01	1.91	1.84
Optimum Detuning [kHz]	+2.3	+2.0	+2.0	+1.8	+1.8
P <sub>cu</sub> [kW] (no margin)	870	862	872	901	952
E <sub>out</sub> [MeV]	21.29	39.11	56.81	73.83	89.91
P <sub>TOT</sub> [kW]	2192	2191	2196	2189	2195

- DTL1 beam commissioning started in the middle of the conditioning campaign.
- High-power conditioning continued till the end of beam commissioning.



# NC Linac Commissioning Highlights

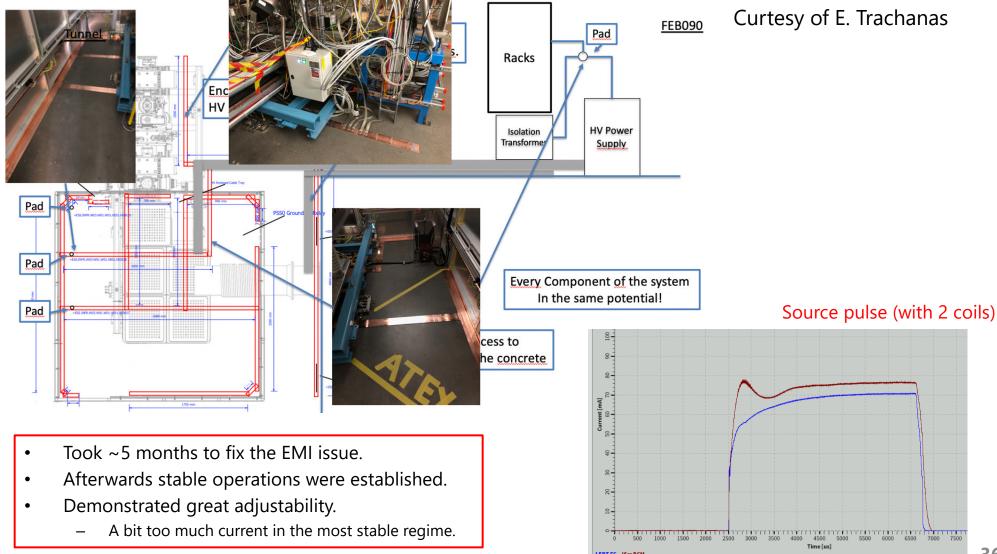
# Single page summary on NCL commissioning



- Nominal 62.5 mA beam through DTL1.
  - No trouble in current ramp-up, despite of missing a log of diagnostics.
    - After resolving the repeller issue.
  - For 62.5 mA, pulth length was limited to 20  $\mu$ s.
    - Most characterization was performed with 5 µs beam.
    - Need a longer pulse to characterize the neutralization effect in LEBT.
- Project strategy for aggressive schedule meant ...
  - Limitations in duty factor and beam power.
    - No temporary beam dump, only FCs.
  - Testing RF with full pulse length has to wait for a long time.
- We ended commissioning in mid-July and went into holidays. Off-line analyses continue after holidays.
- Peak performane of hardware is good so far.
- But, we need to improve availability and operations.
  - Frequent reconditioning of buncher cavities for very low power.
    - Instability during the ramp due to multipacting.
  - Need to improve management of systems configurations.
  - Need to fine-tune processes and procedures.

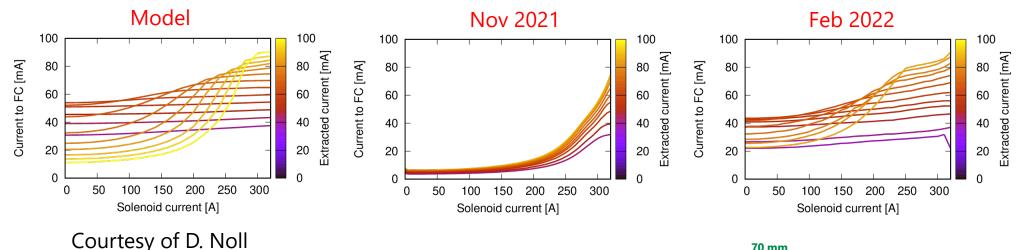
# Source needed grounding improvements for EMI



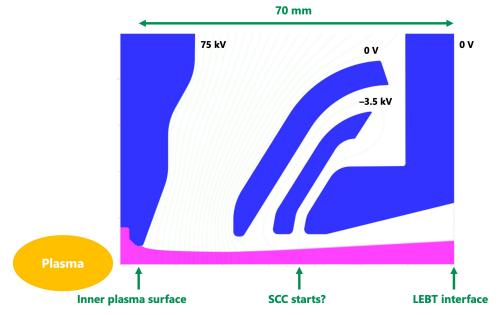


### ISrc repeller was discovered to be disconnected





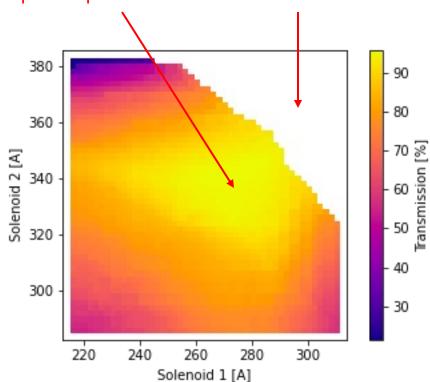
- It was found that the ISrc repeller was not conntected during maintenance in Jan 2022.
  - Not straighforward to measure voltage on a capacitor.
- The ISrc behaviour much close to the model.
- Unfortunately most data from 2019 and 2022 became useless (including emittance) and we're back to the squre-one.



# Tuning LEBT and RFQ

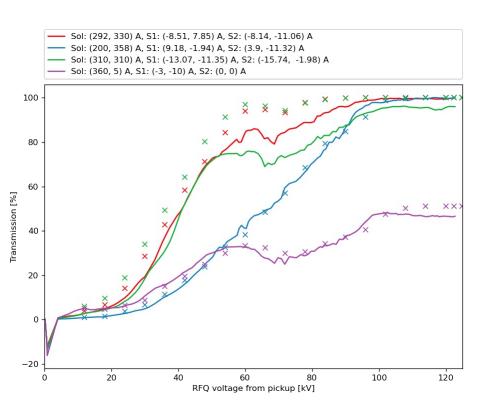






#### LEBT solenoids scan:

 Best transmission = best emittance preservation



#### RFQ voltage scan

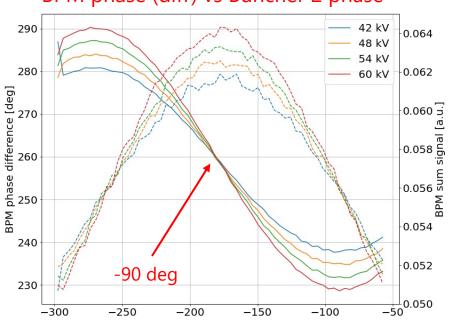
- Only degrees of freedom
- Good matching to the model against the reconstructed distribution

# Cavity amplitude and phase setting

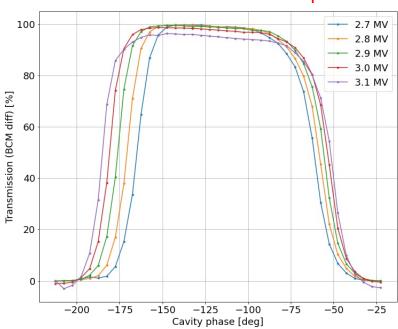
- Major activies during commissioning and start-ups







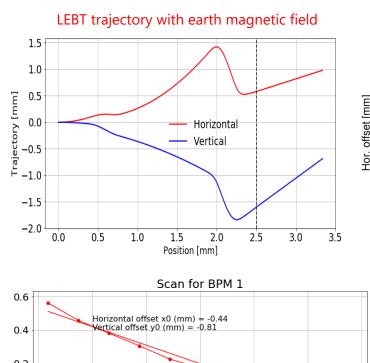
#### DTL1 transmission vs DTL1 phase

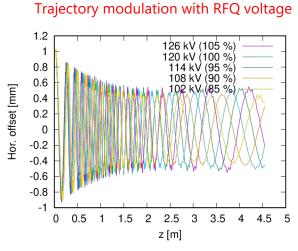


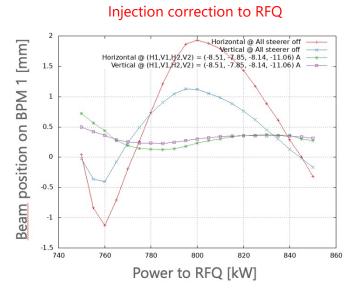
- Synchronizations of cavities have to be established one by one from the downstream side.
- "Phase scan": scan a cavity phase and look and BPM phase (time-of-flight).
  - Check the energy or the pattern ("signature matchig").
  - Also provide beam based calibration of amplitude, e.g., Buncher 3 was off by ~10%.
- For DTL1, we can do the same with transmission vs phase.

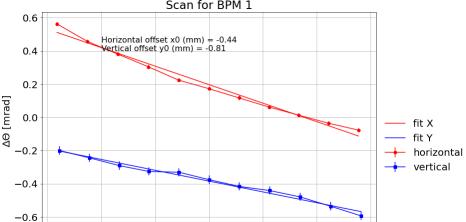
### Beam trajectory











5

10

15

- Beam steering is not as important for a ring.
  - As long as there's no loss.
- Earth magnetic field (~47 μT downward) has a large impact in LEBT.
  - Injection correction to RFQ for modulated RFQ voltage.
  - Not so much attentioned paid to steering in MEBT and DTL1, due to a good transmission.
    - Beam-based alignment tried for a few BPMs in MEBT.

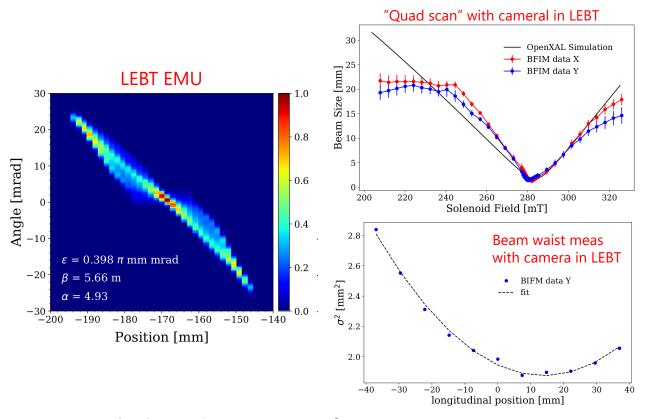
Δk

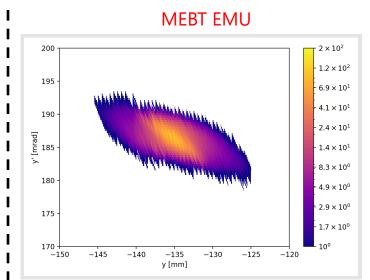
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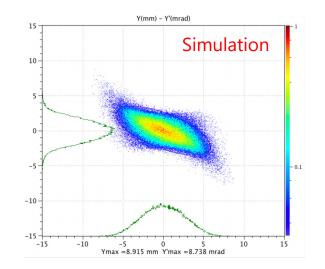
#### **Emittance**





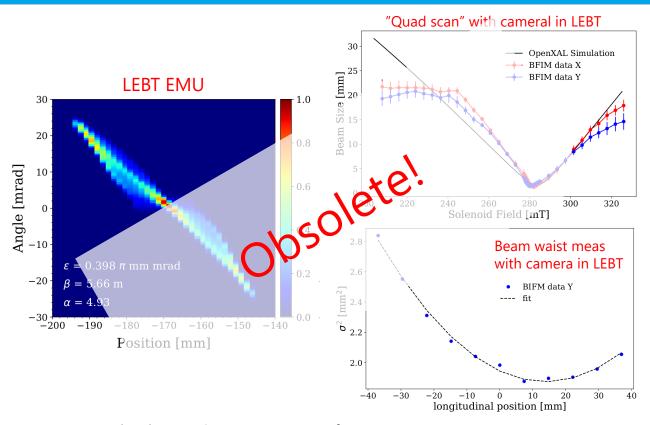


- 3 methods consistent (10-20%) for LEBT.
  - Instruments not available after the IS-LEBT commissioning.
  - Data no longer vaild. (Repeller issue)
- MEBT EMU (V-plane) became available during last ~1 week.
  - Preliminar result shows  $\sim 0.5 \, \pi$  mm mrad. (Sensitive to how to cut noise, as usual.)
  - Beta off by -30%, alpha -0.2.
  - H-unit became available on the last day and showed a similar value.



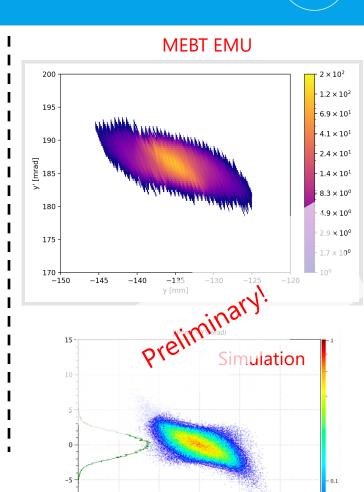
#### **Emittance**







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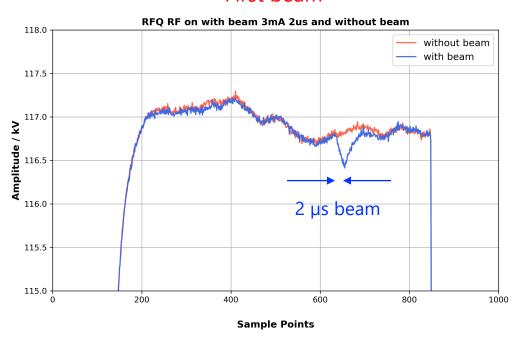
Ymax =8.915 mm Y'max =8.738 mrad

-10

#### **LLRF**

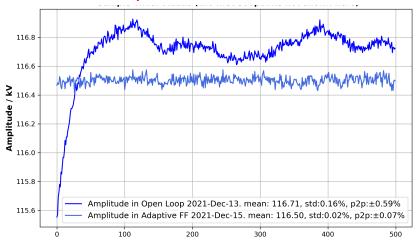


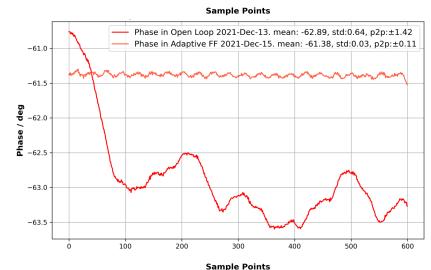
#### First beam



- Feedback and feed-forward are not yet finalized and still under testing.
- Peak-to-peak flatness ~0.5% (due to the modulator?)
  - Requirement: 0.2% in RMS after the first 10 μs.
- Beam loading  $\sim$ 0.5% for 3 mA and 2  $\mu$ s beam.

#### Script based feed-forward







# Summary

# Single page summary on ESS project and linac



- European Spallaton Source (ESS) is ...
  - Under construction in Lund, Sweden.
  - User program from 2025.
  - Driven by a high-power proton linac.
    - Normal-conducting linac (NCL) + superconducting linac (SCL).
    - No accumulator ring.
    - Design: 2 GeV and 5 MW
    - Initial operations (with limited RF source): 800 MeV and 2 MW
  - Upgrade study ongoing for neutrino program
    - Upgrade to 10 MW.
    - Proton and H- in parallel.
    - Accumulator ring.
- NCL
  - Full current beam (62.5 mA) through DTL tank 1 (out of 5).
    - Commissioning with minimal systems so far from completed.
  - Commissioning to DTL tank 4 next year.
- SCL
  - Installations and testing in the tunnel and garally progressing (RF, cryo, controls, ...)
  - Manufacturing and testing of superconducing cavities and cryomodules ongoing.

# Single page summary on NCL commissioning



- Nominal 62.5 mA beam through DTL1.
  - No trouble in current ramp-up (after resolving the repeller issue).
- Project strategy for aggressive schedule meant ...
  - Limitations in duty factor and beam power.
    - No temporary beam dump, only FCs.
  - Testing RF with full pulse length has to wait for a long time.
- We ended commissioning in mid-July and went into holidays. Off-line analyses continue after holidays.
- Peak performane of hardware is good so far.
- But, we need to improve availability and operations.
  - Frequent reconditioning of buncher cavities for very low power.
    - Instability during the ramp due to multipacting.
  - Need to improve management of systems configurations.
  - Need to fine-tune processes and procedures.



# Thank you for your attentions!