Beam Commisssionimg of Normal-conducting Part
and
Status of ESS Project

Ryoichi Miyamoto (ESS)
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LINAC 2022 MO1PA02

On behalf of many ESS stuffs and collaborators…

BEAM COMMISSIONING OF NORMAL CONDUCTING PART AND STATUS OF ESS PROJECT

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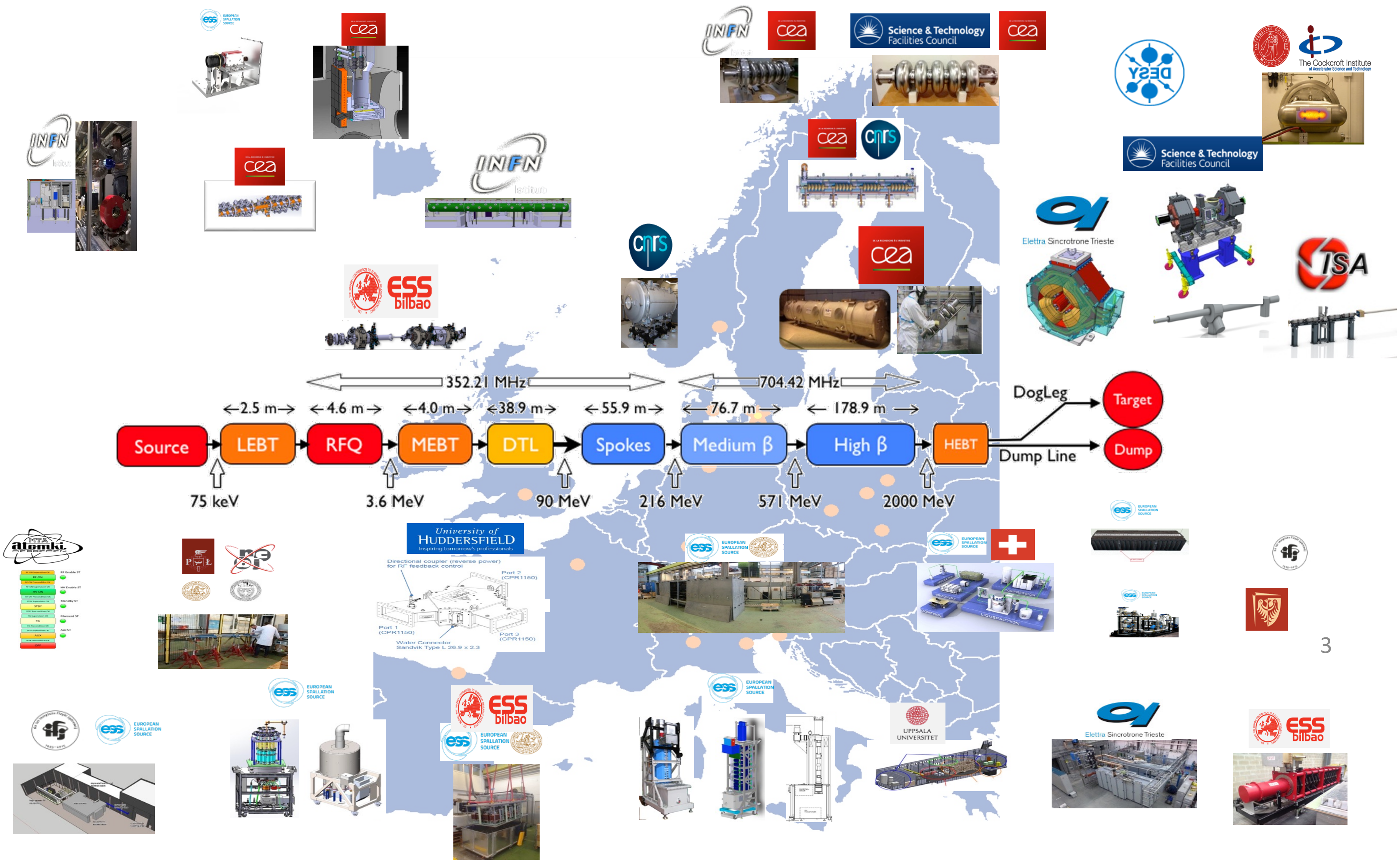
ESS linac project as European collaboration
>20 institutions (A. Jansson IPAC22-TUIYGD1)

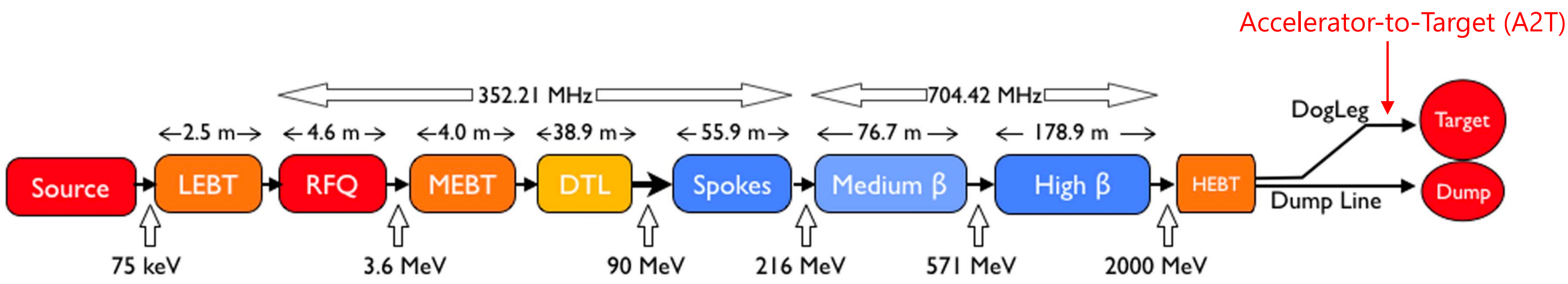


Outline

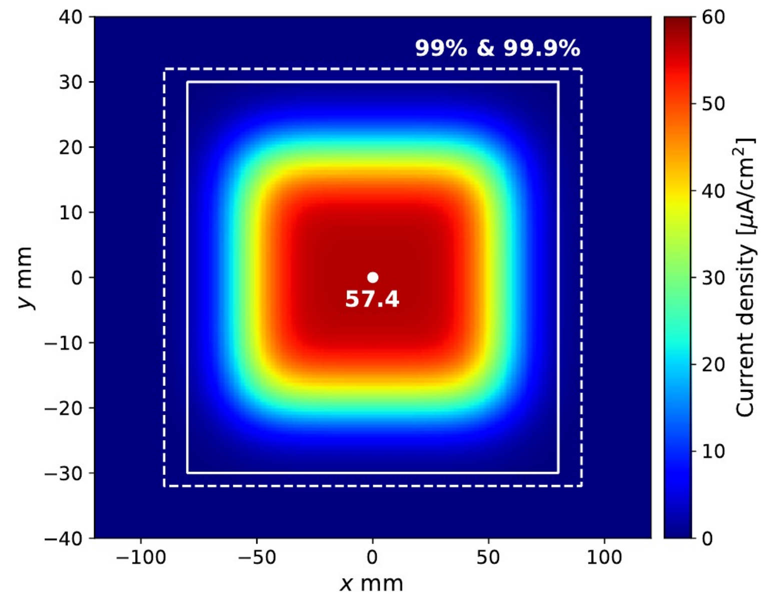
- ESS linac and commissioning overview
- Recent project highlights
- Normal-conducting linac commissioning
  - Normal-conducting sections
  - Highlights
- Summary

ESS Linac and Commissioning Overview

ESS linac design: High-level parameters

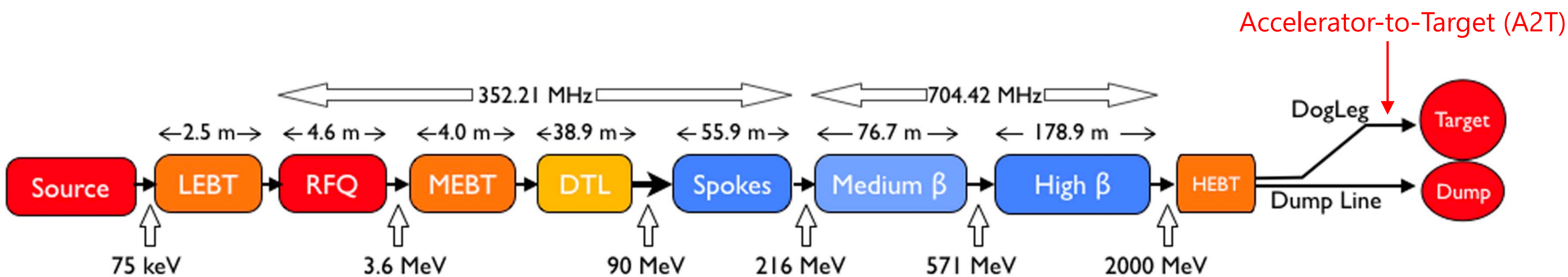


Parameter	Value
Ave power (design) [MW]	5
Max energy (design) [MeV]	2000
Peak current [mA]	62.5
Pulse length [ms]	2.86
Rep rate [Hz]	14
Duty factor [%]	4
RF freq [MHz]	352.21/704.42



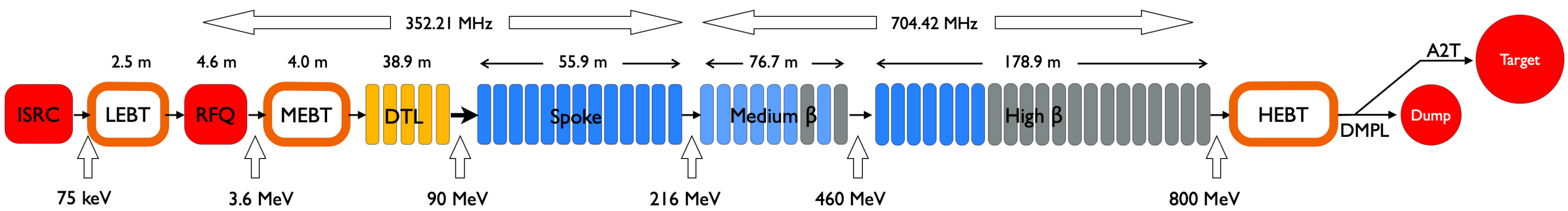
Beam footprint on target by raster system in A2T

ESS linac design: Lattice structure



	Length	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 I (~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	—	1	—	Elettra
A2T	44.7	6 Quads + 8 Raster	—	1		Aarhus Uni
	603.0					

ESS linac during the initial operations (~2026)



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

- 7 medium-beta cryomodules (CMs) (out of 9).
- 7 high-beta CMs (out of 21).
- For the first beam on target, 2 high-beta and 570 MeV.
- All CMs will be installed, just RF missing.
- Brightest neutron source with >2 MW.
  - Moderator design.

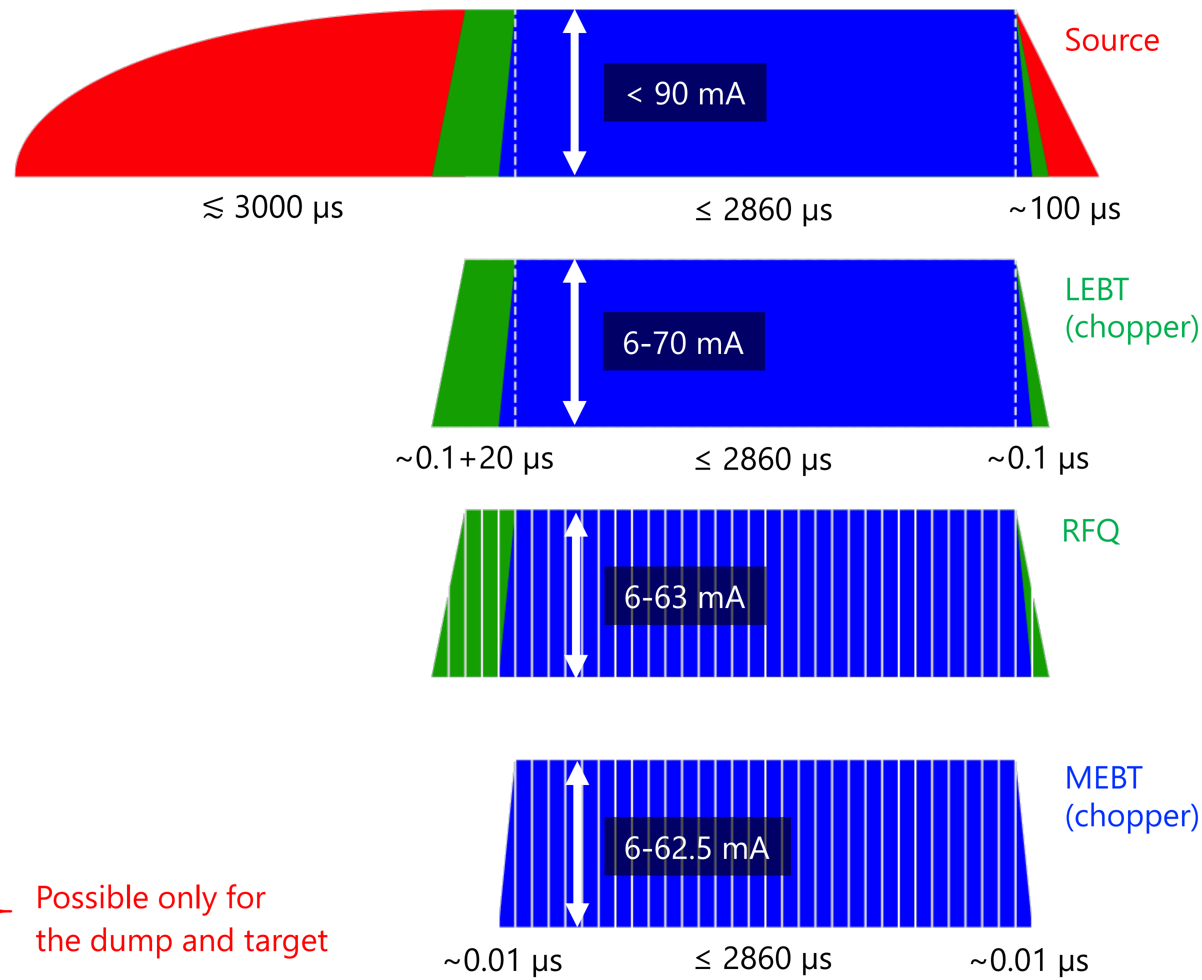
Beam pulse time structure
Slow and fast choppers in LEBT and MEBT

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

Possible only for the dump and target

Time structure defined in front-end

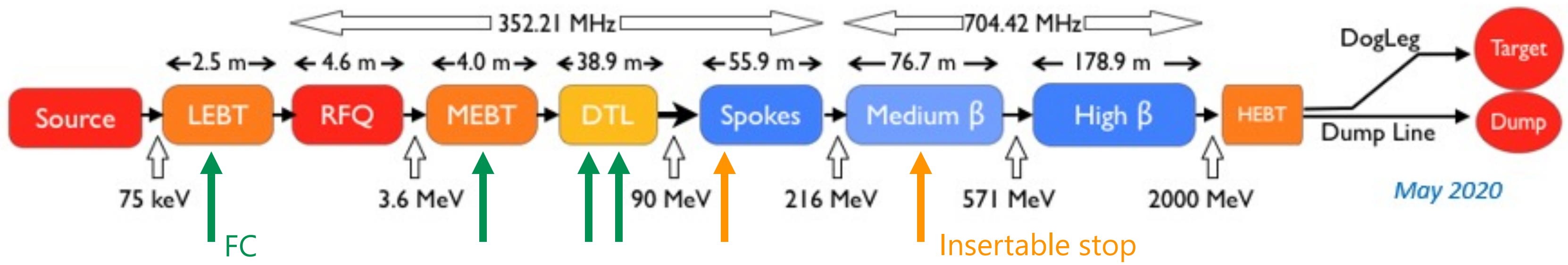


Commissioning strategy and where we are

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	2023-06	2020-04-27	2019-01-24
Dump	2024-07 (570 MeV)	2024-10	2021-02-08 (570 MeV)	2019-05-13 (2 GeV)
Target	2025-04 (570 MeV)		2022-06-08 (1370 MeV)	2019-06-24 (2 GeV)

- Because of the aggressive schedule (start time and duration)…
  - No temporary stop nor diagnostics after the source+LEBT.
    - The biggest pulse during the commissioning is 62.5 mA and 50 μs.
  - Instead to include comprehensive set of permanent diagnostics throughout the linac.
  - All commissioning step started ASAP with the minimal systems.
    - e.g., with FCs, BCMs, and BPMs for the MEBT step.
  - The main goal to sent low power beam to the end verify all the systems.

Beam stops and diagnostics



Device	Type	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 transverse				7	15	14	9	21	16	12	4	98
Non-invasive profile			2		2		1	3	1		1		10
Imaging	Parasitic target/dump transverse										2	1	3
Grid											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

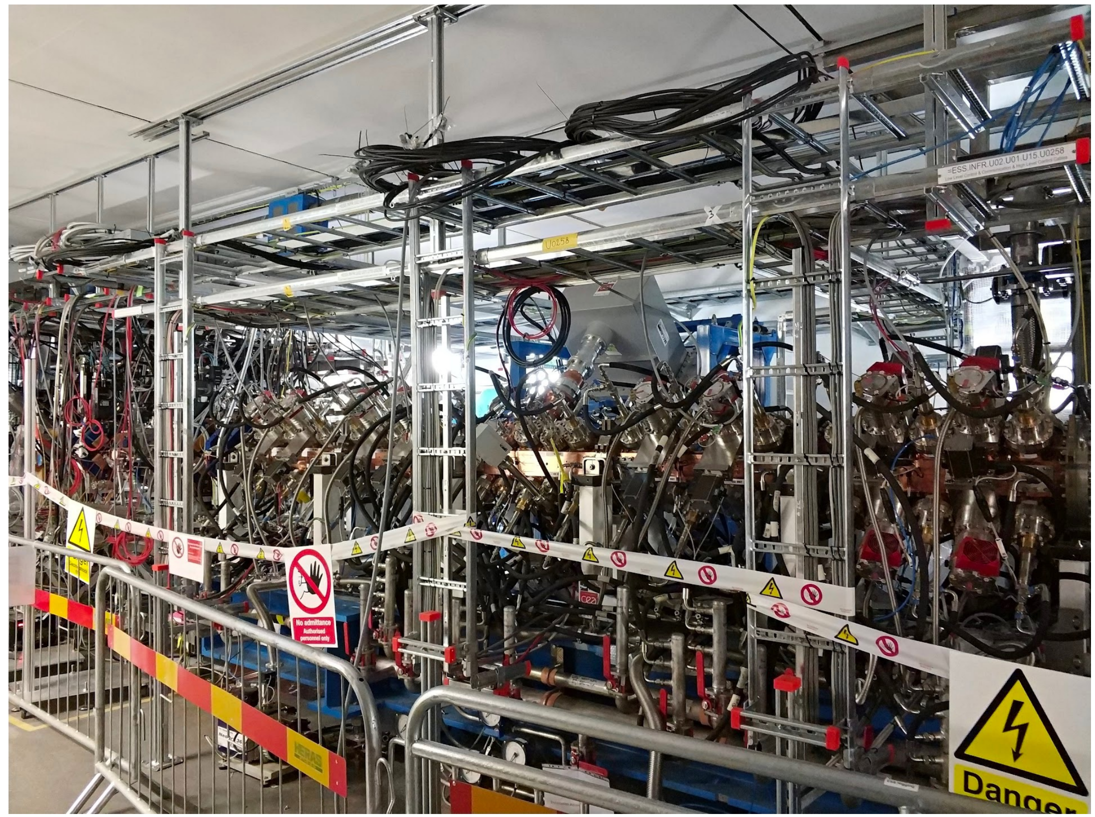
Recent Project Highlights

Recent highlights in one page
Conbributions in this conference

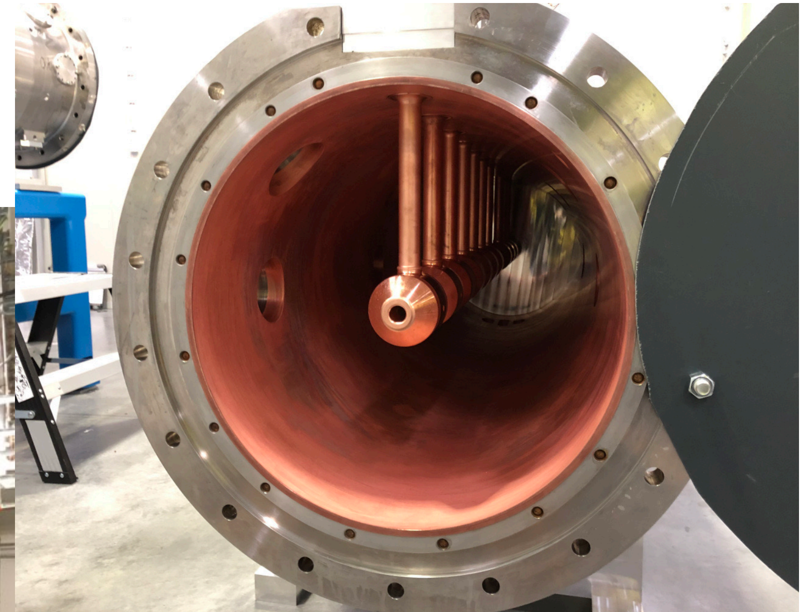
- Normal-conducting linac (NCL)
  - RFQ conditioning (2021)
    - 850 kW (116% of the nominal) for the full duty factor.
    - R. Zeng TUPOPA05
  - DTL1 conditioning (2022)
    - 3.15 MV/m (105% of the nominal) for ~1 ms and 14 Hz.
    - F. Grespan TUPOJO09
  - Nominal curreent (62.5 mA) beam to the DTL1 exit, in July 2022.
- Superconducting linac (SCL)
  - Cryo distribution system installation completed, followed by testing.
  - Manufacturing and testing of cavities and cryomodules ongoing.
    - Maiano TH1PA02
  - Cryomodules are being delivered to ESS. Installation will start next year.
    - So far, 8 spoke, 7 medimum-beta, and 2 high-beta.
    - Maiano TH1PA02
  - RF system testing and installation are ongoing.

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

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



DTL tank 1



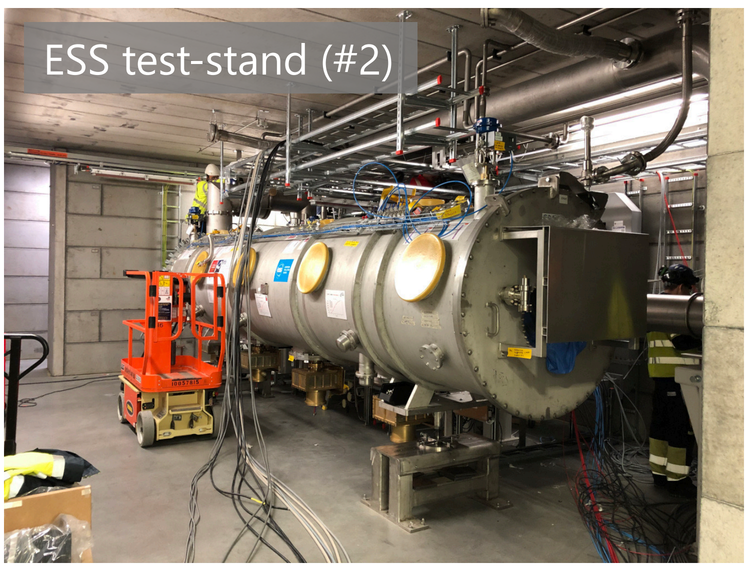
RF systems

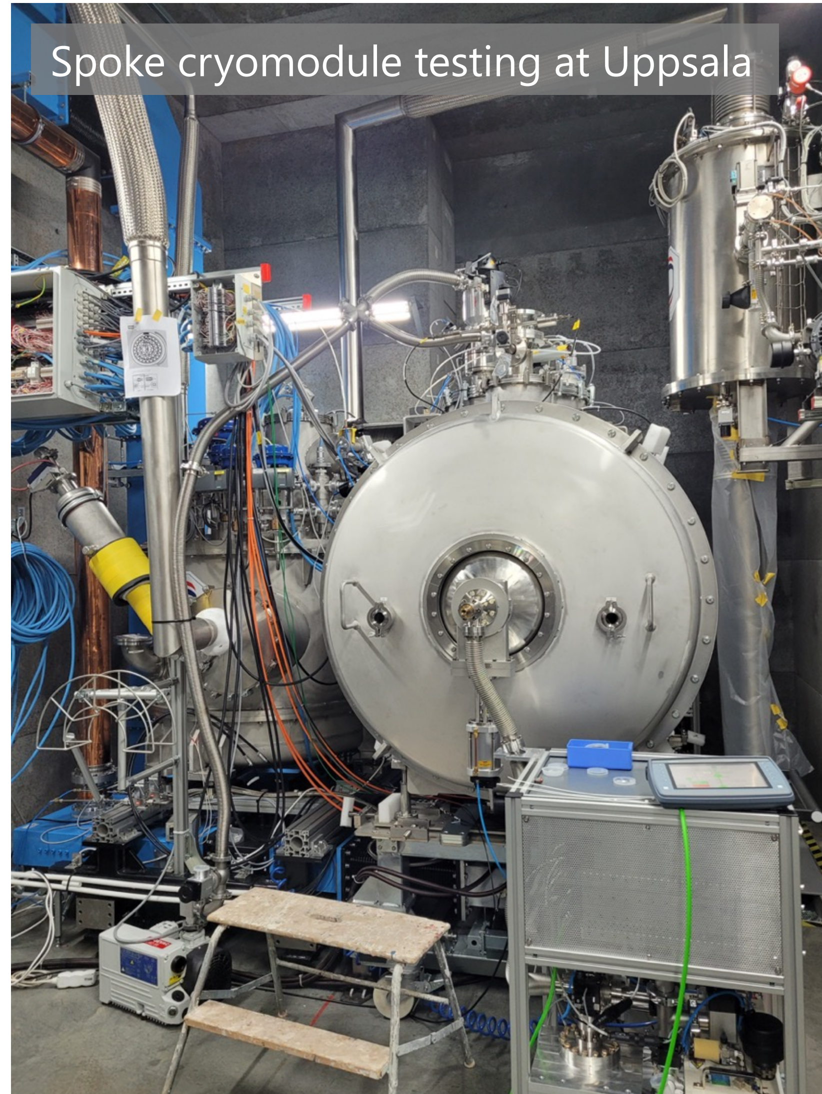
Operational for NC linac

Installation and testing ongoing for SCL

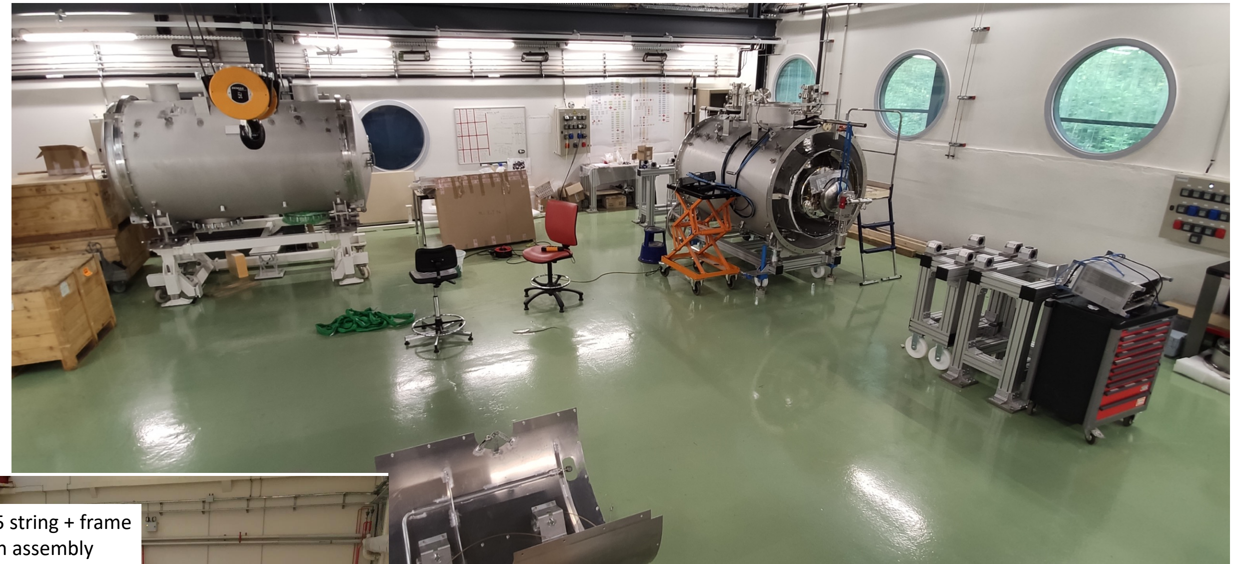
SC cavities and cryomodule testing ongoing


High-beta cavity testing at STFC


ESS test-stand (#2)


Spoke cryomodule testing at Uppsala

Cryomodule assembly ongoing at in-kind



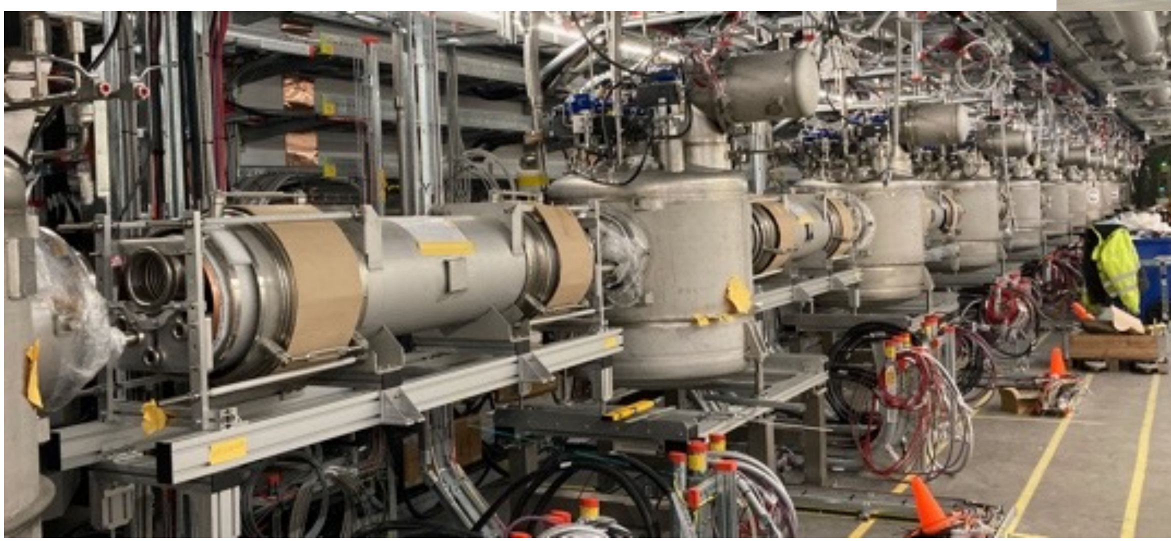
Spoke cryomodules at IJC-Lab

Elliptical cryomodules at CEA

Cryomodules delivered to the ESS site
So far 8 spokes, 7 medium-beta, and 2 high-beta

Cryo system

Distribution system installation just completed



Test ongoing for years

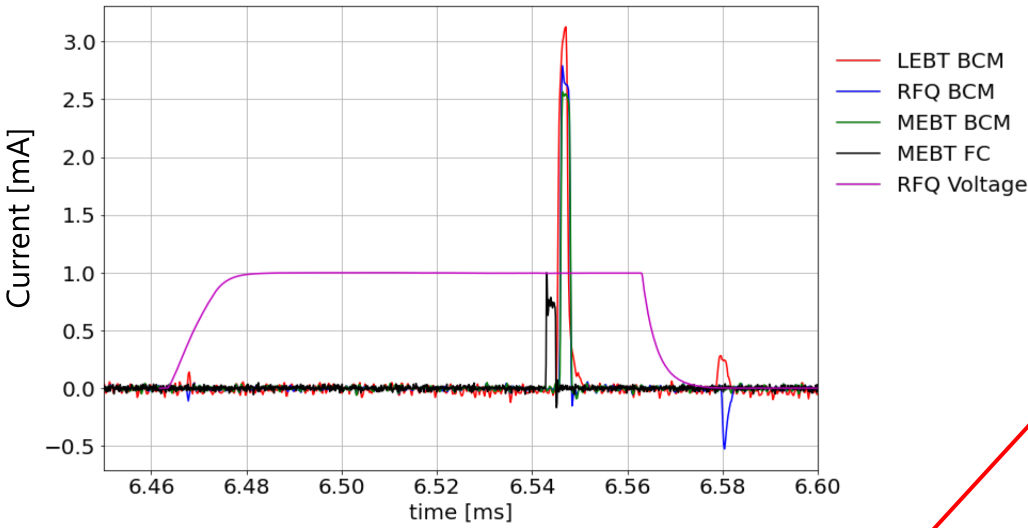
Very first beam on the ESS site, 2018-09-19

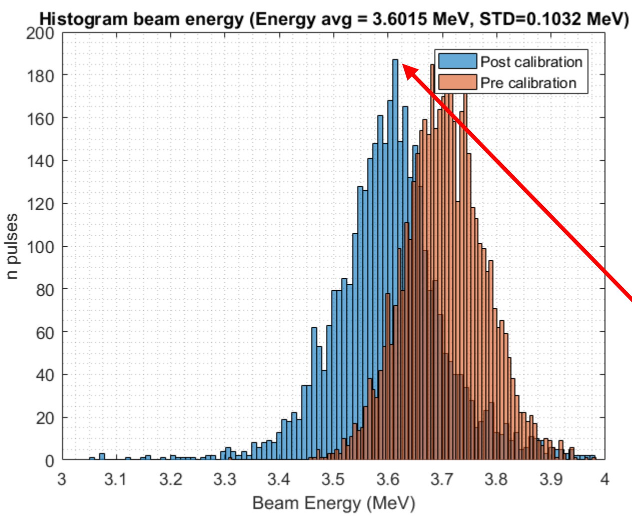
Logbook message ID 69, 2018-09-19 10:31

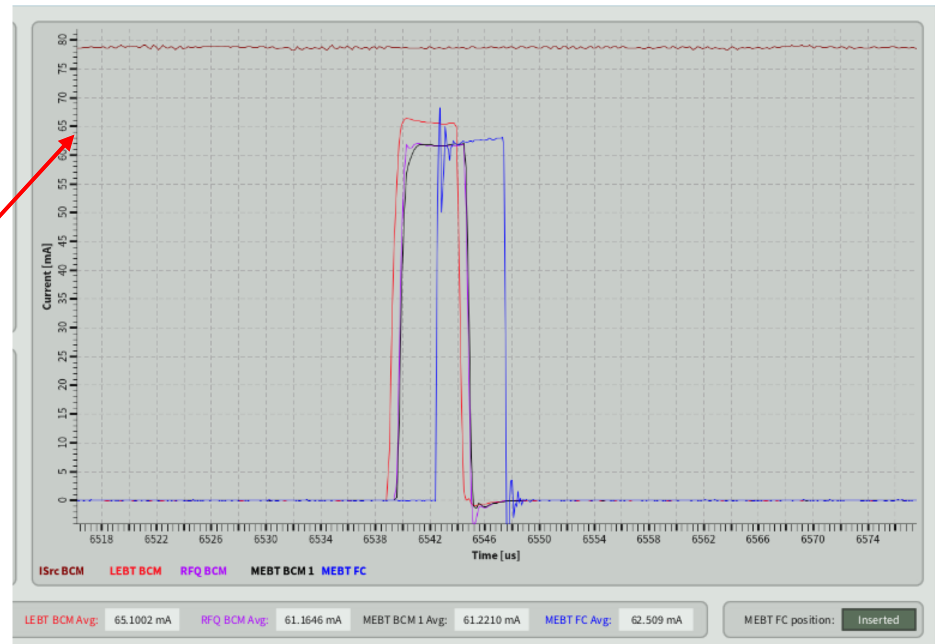
Ryoichi on behalf of ISrc team.

"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



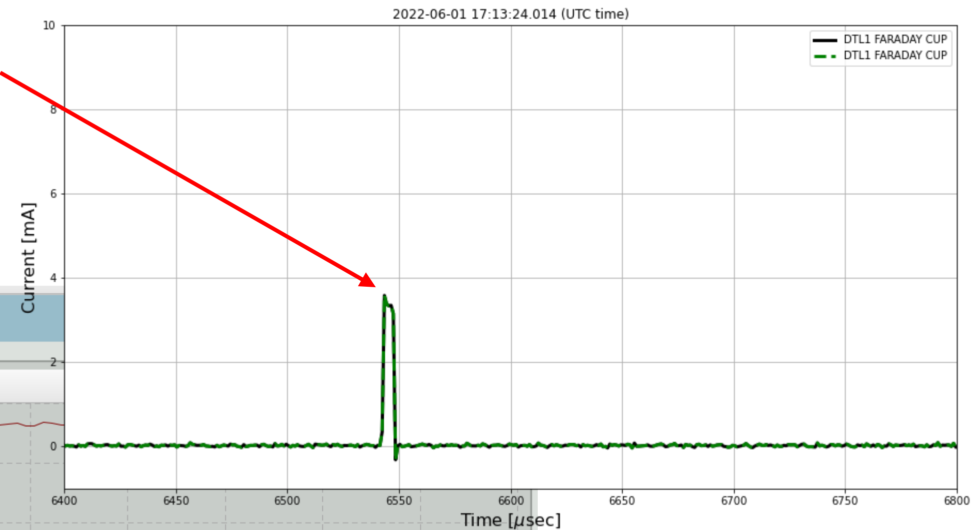


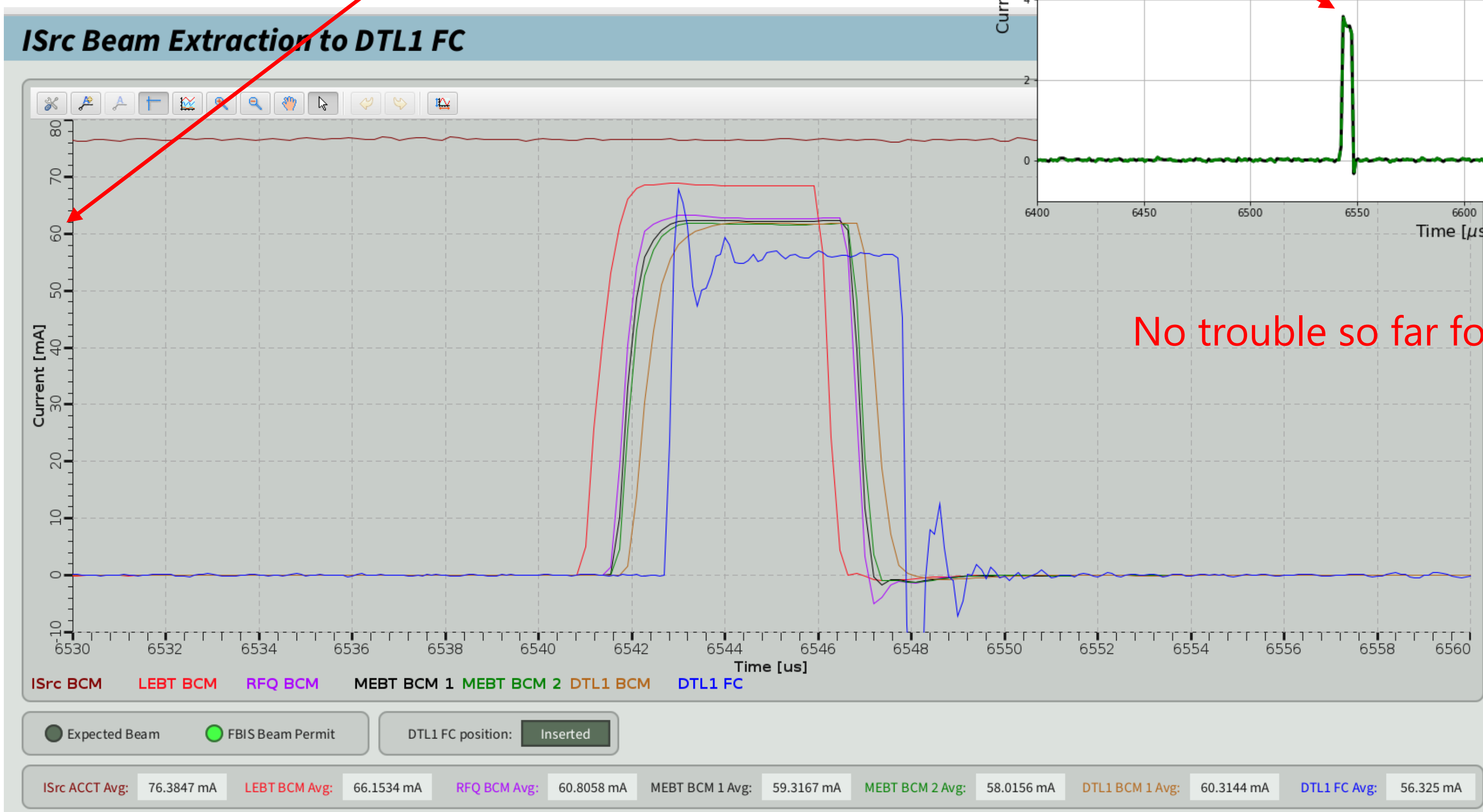


65 mA

3.60 MeV
(Direct energy measurement with ToF)

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





No trouble so far for current ramp-up.

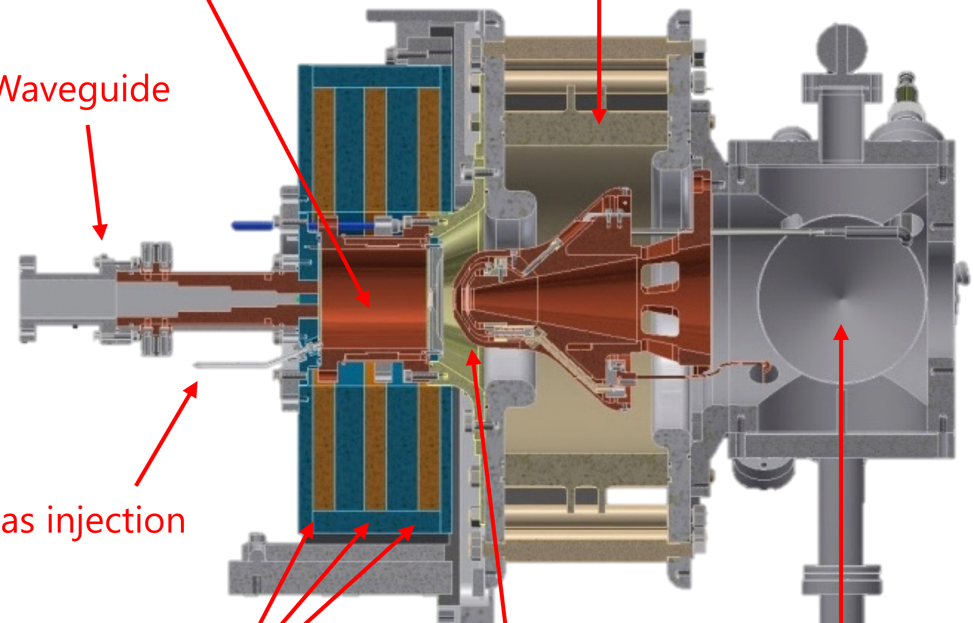
End of DTL1 commissioning

NCL Sections

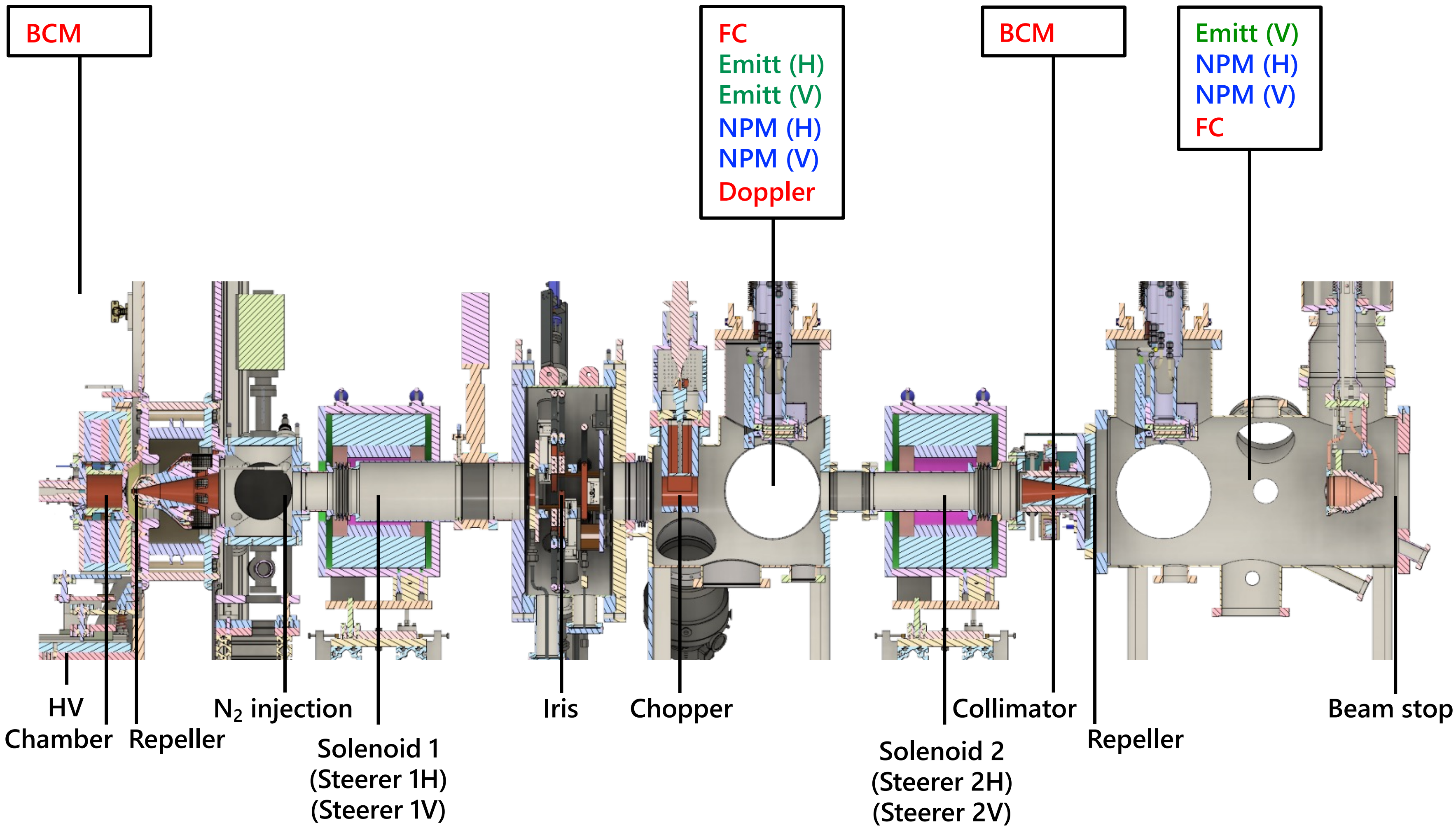
ESS microwave discharge source

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

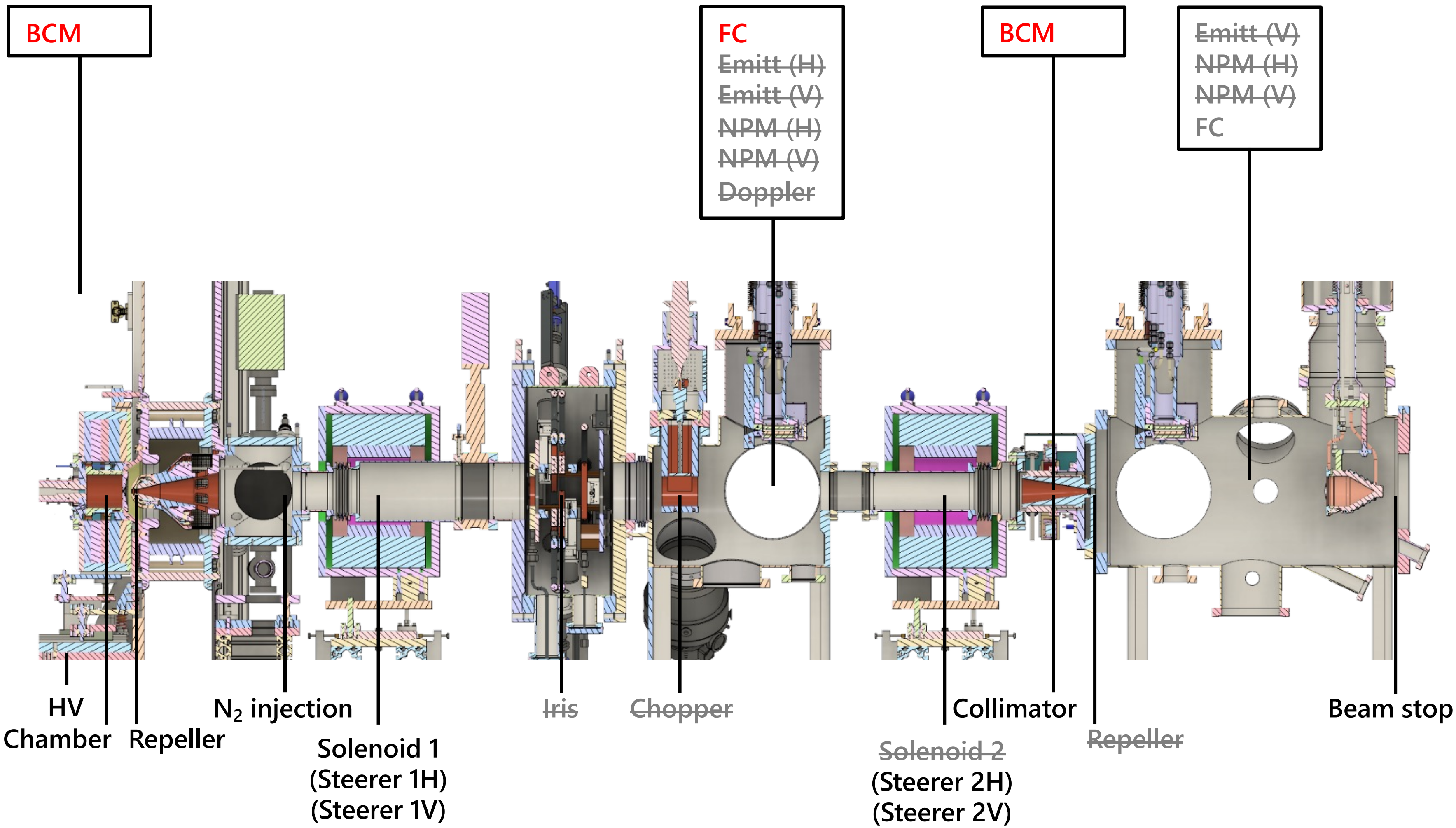
- 5 Primary knobs:
  - RF power
  - H2 flux
  - 3 solenoids (coils) => great flexibility



LEBT systems during beam commissioning

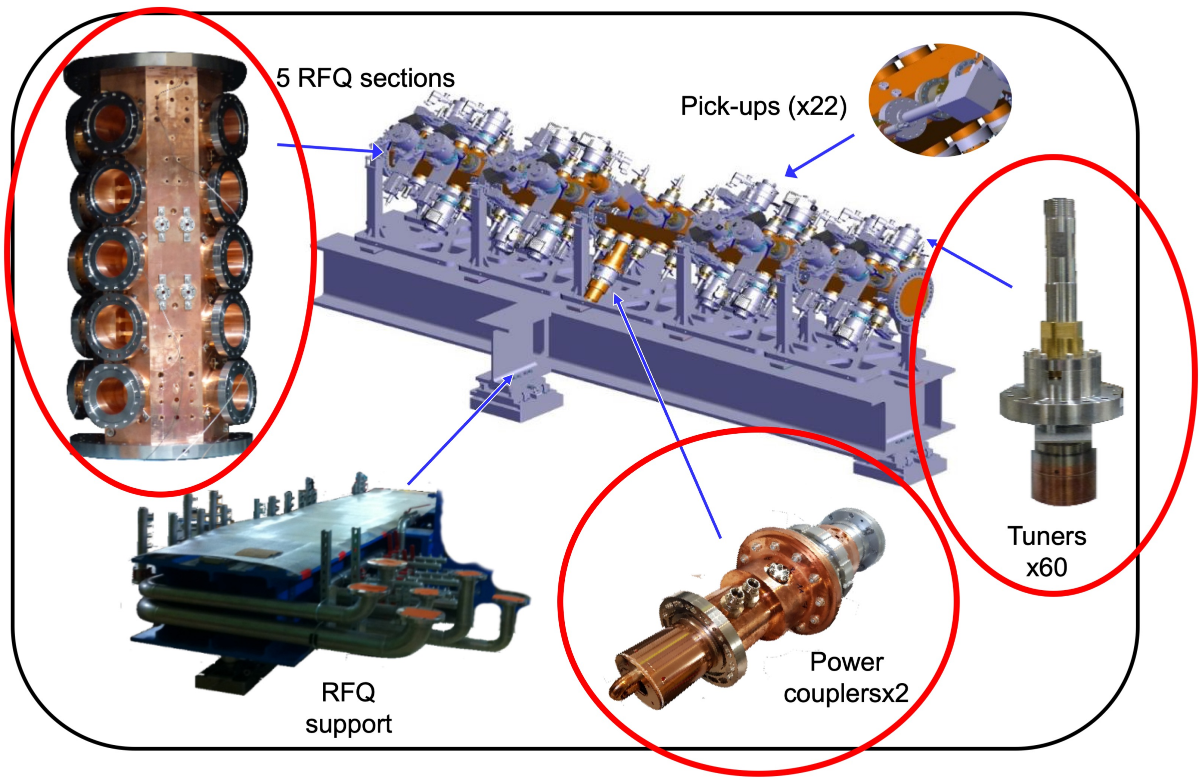


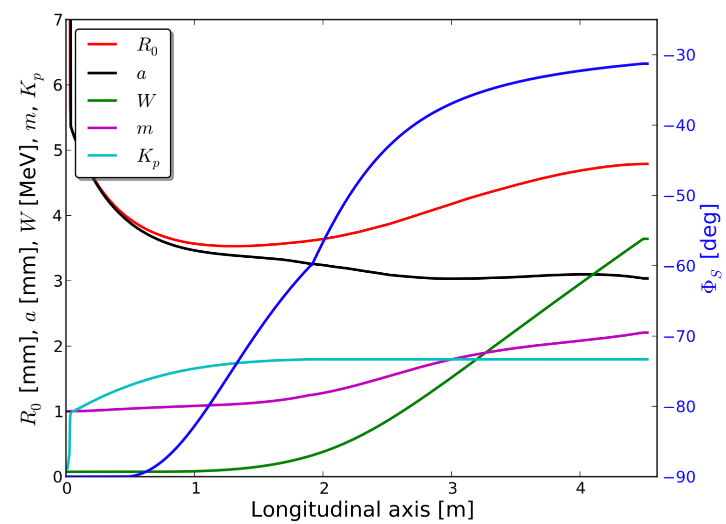
LEBT systems at the restart



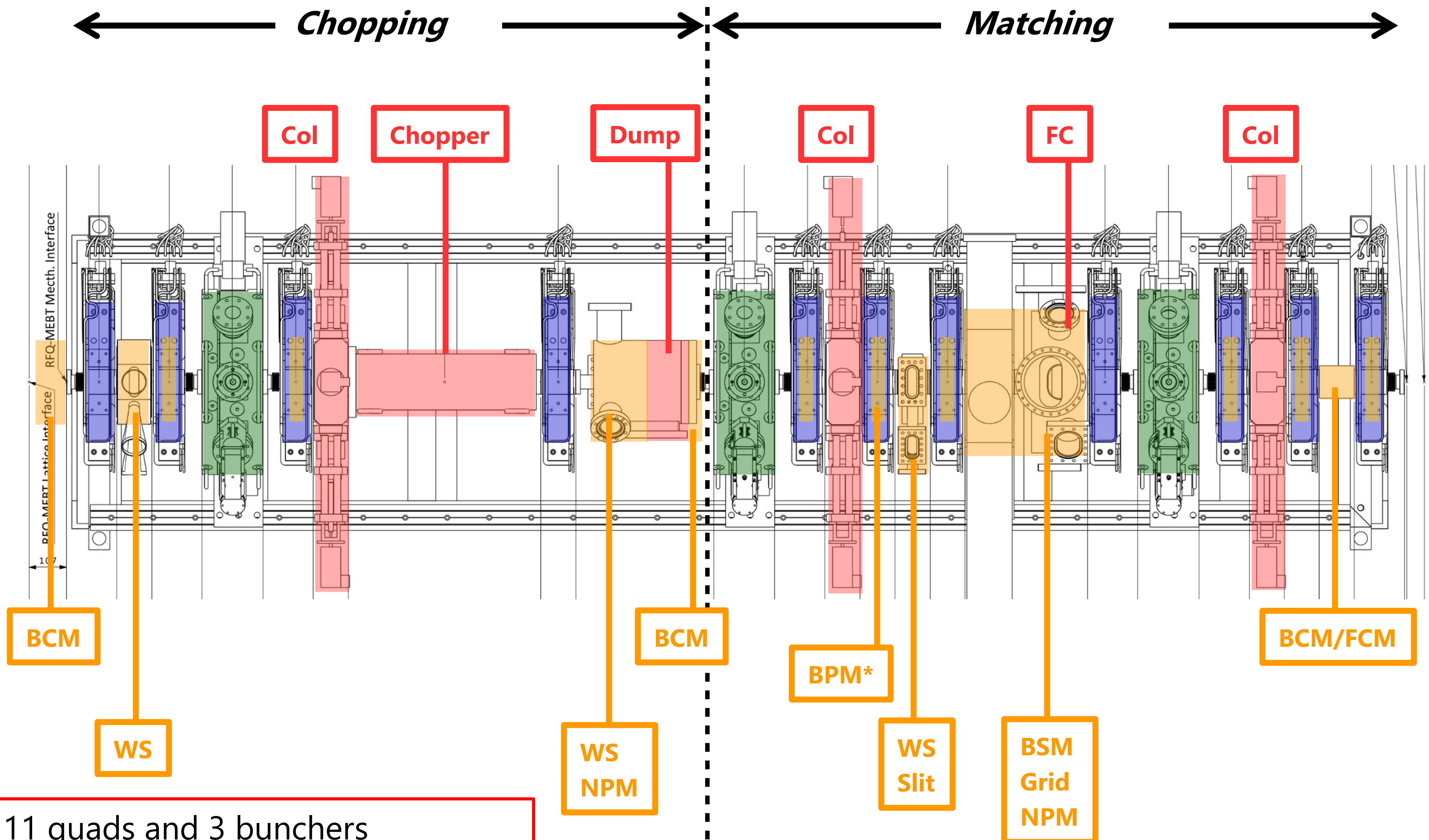
ESS RFQ

- The ESS RFQ in numbers
  - **75 keV to 3.62 MeV**
  - 4.6 m long
  - 4 vanes
  - 2 coaxial power couplers
  - 5 segments
  - 22 field pickups
  - 60 static tuners
  - 66 cooling circuits
  - 80-120 kV intervane voltage
  - 352.21 MHz





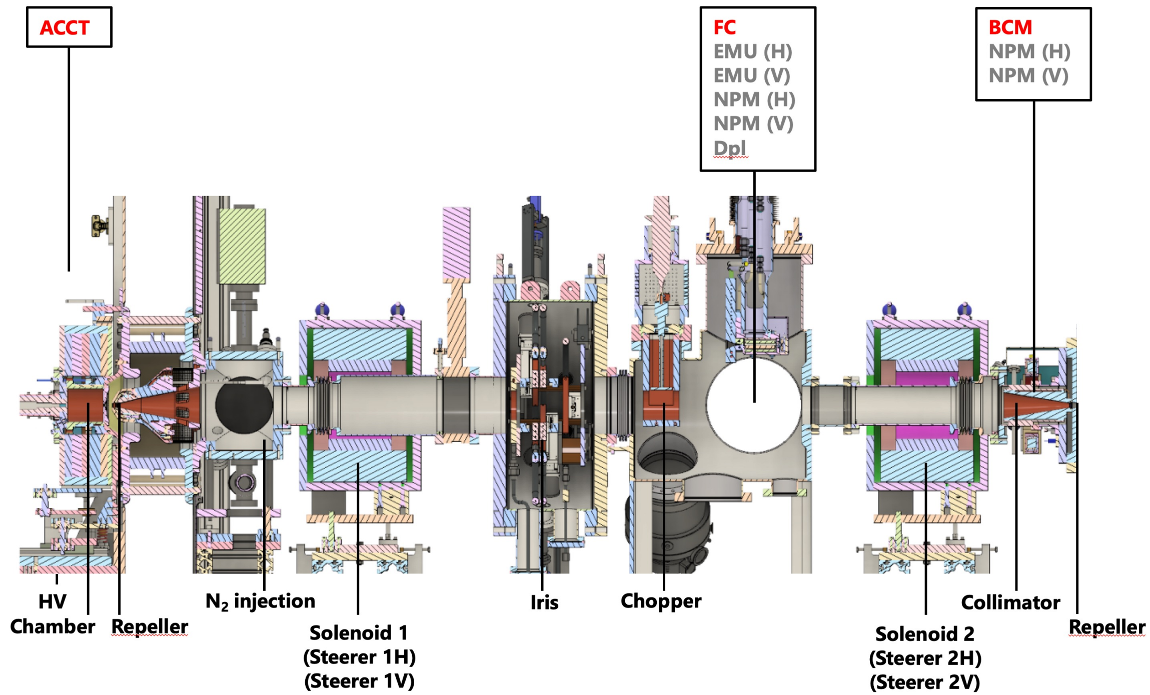
ESS MEBT

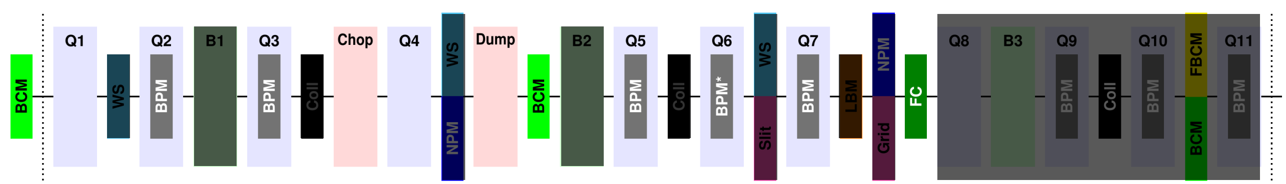


- 11 quads and 3 bunchers
- Fast chopping and characterization

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_0 [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
ϕ_s [deg]	**-35,-25.5**	-25.5	-25.5	-25.5	-25.5
L_{Tank} [m]	**7.62**	7.09	7.58	7.85	7.69
Diam Tank [mm]	**521**	521	521	521	521
R_{Bore} [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_{PMQ} [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_{cu} [kW] (no margin)	**870**	862	872	901	952
E_{out} [MeV]	**21.29**	39.11	56.81	73.83	89.91
P_{TOT} [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.

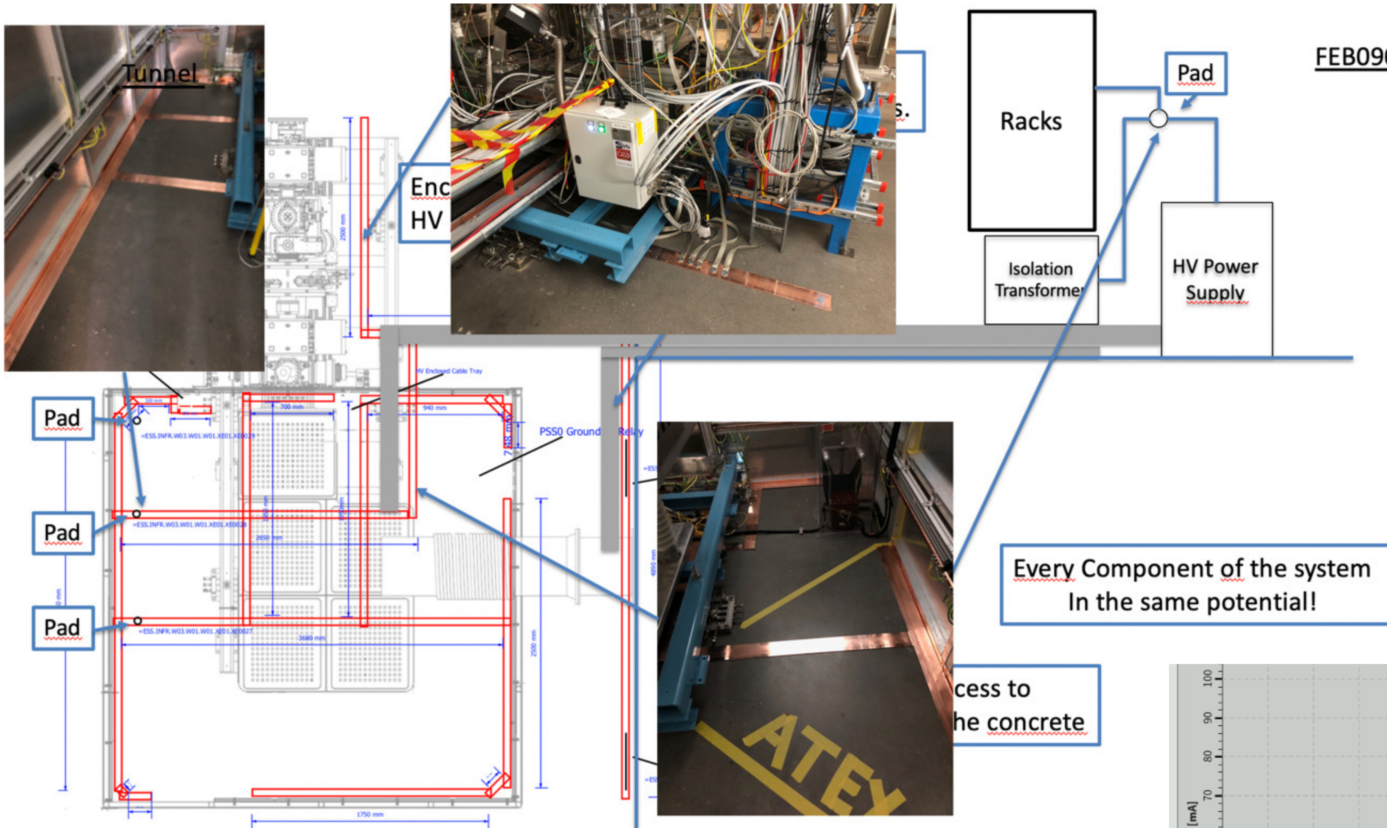
NCL Commissioning Highlights
(Mainly Beam Characterizations)

Contributions related to NCL commissioning

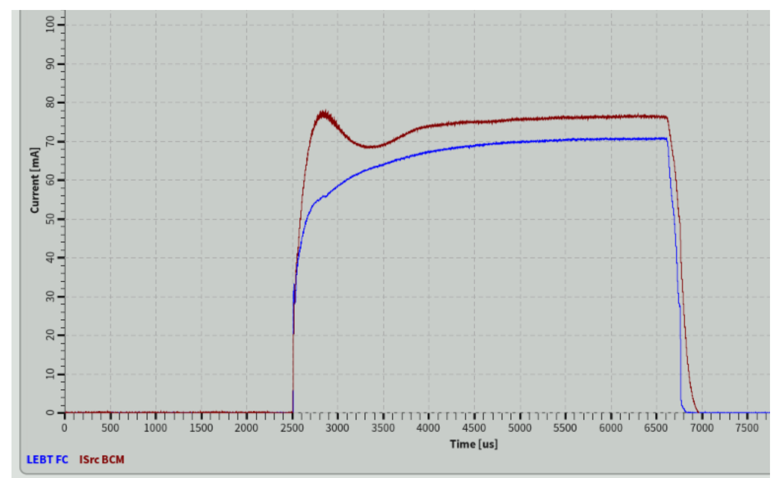
- LINAC22
  - Source
    - L. Neri THPORI19
  - LEBT beam dynamics
    - L. Bellan TUPORI29
  - RFQ beam dynamics
    - D. Noll TUPOPA04
  - Hardware commissioning
    - B. Jones TUPOJO10
  - MEBT
    - A. Sosa TUPOJO14
  - WS commissioning
    - C. Derrez TUPOJO13
  - MPS
    - S. Gabourin MOPORI17
- IBIC22
  - MEBT beam dynamics
    - N. Milas MO2C2
  - Phase scan
    - Y. Levinsen TUP35

Source needed grounding improvements for EMI

Curtesy of E. Trachanas



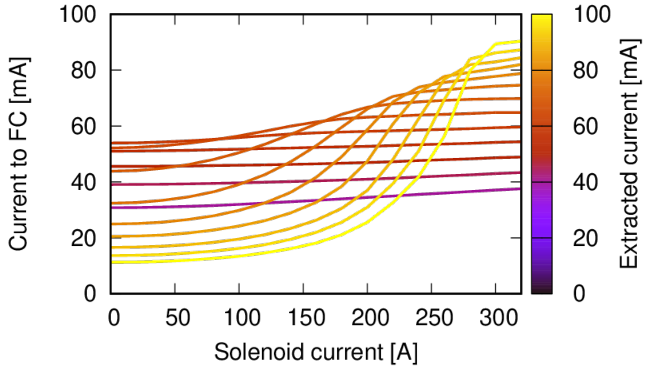
Source pulse (with 2 coils)



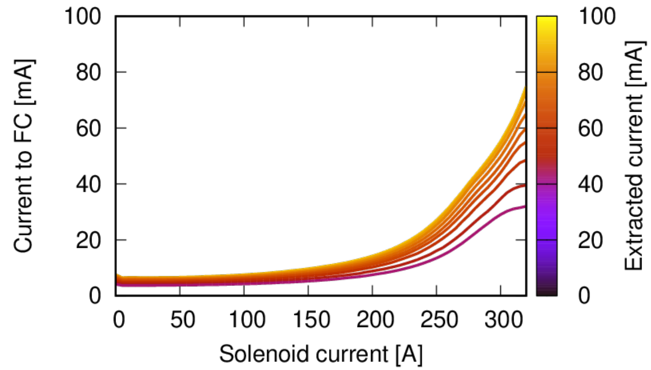
- Took ~5 months to fix the EMI issue.
- Afterwards stable operations were established.
- Demonstrated great adjustability.
  - A bit too much current in the most stable regime.

ISrc repeller was discovered to be disconnected

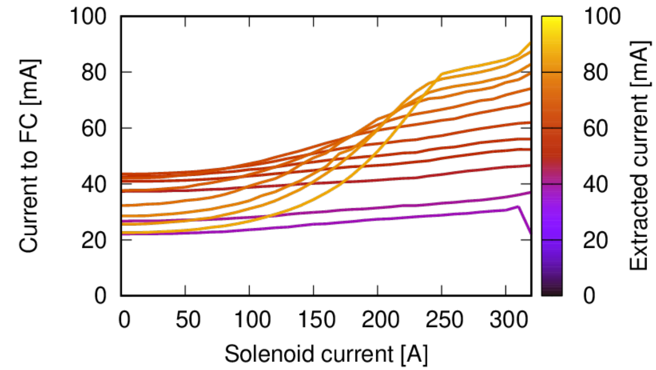
Model



Nov 2021

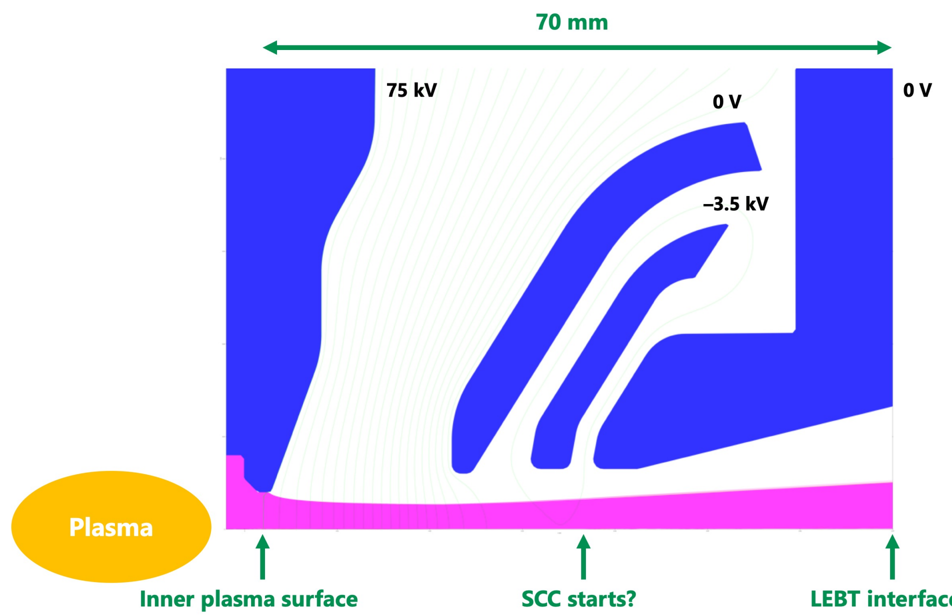


Feb 2022

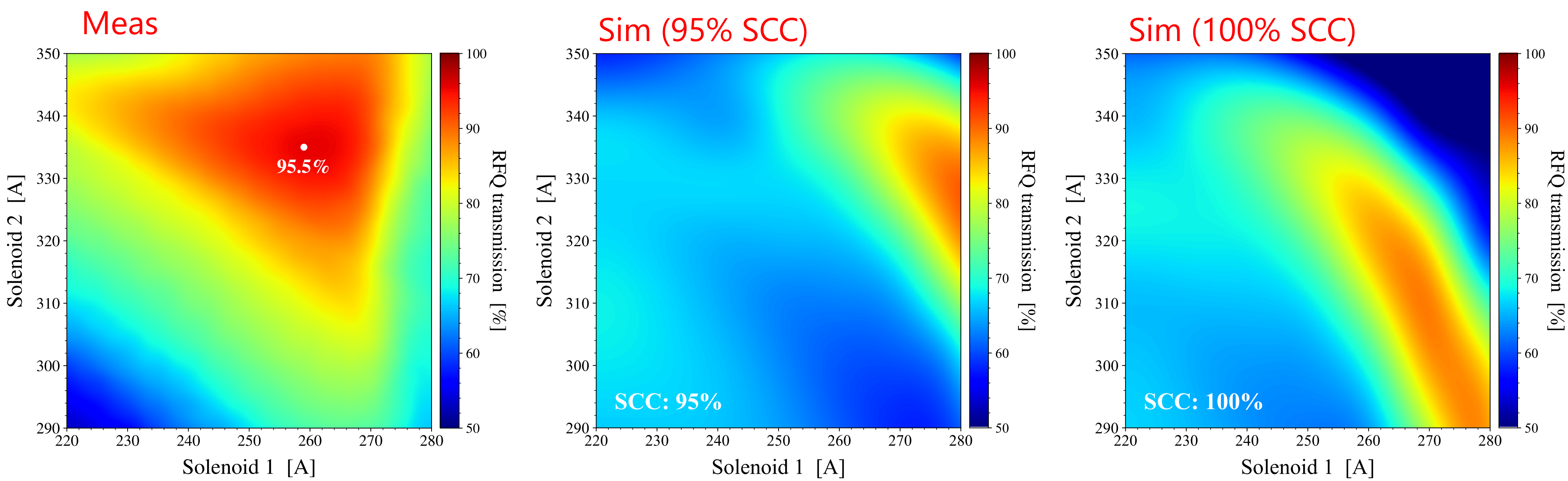


Courtesy of D. Noll

- 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.

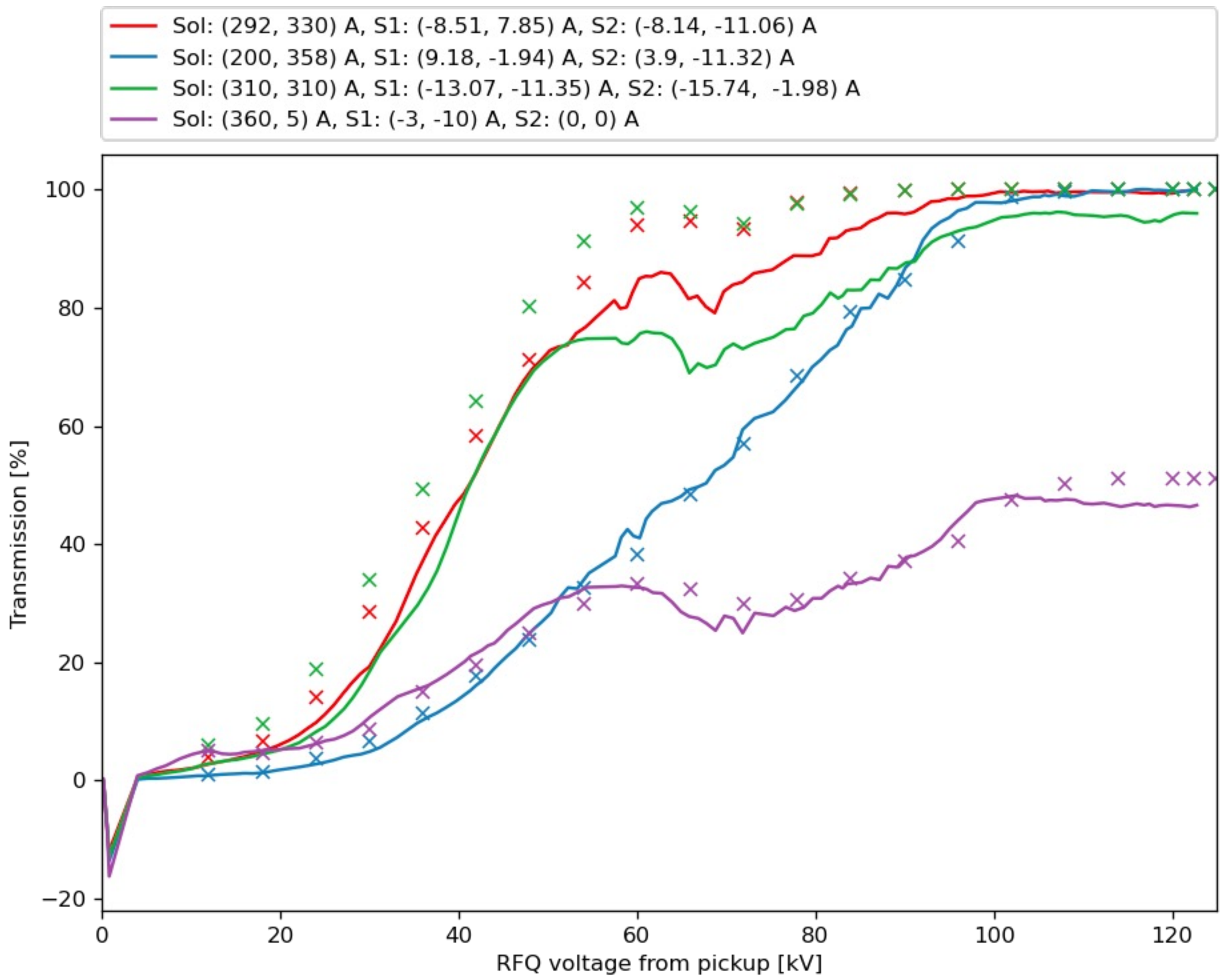


Solenoids scan (preliminary)



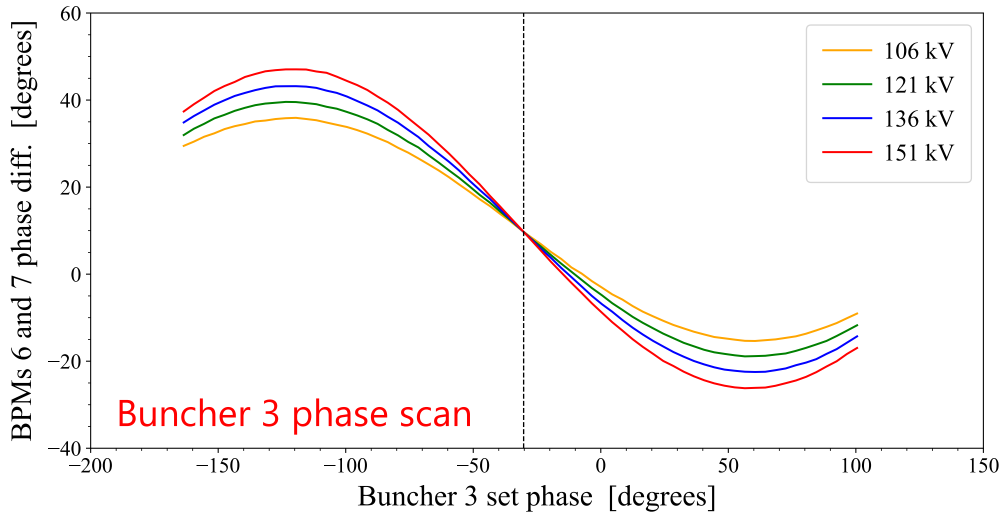
- Best transmission = best beam quality preservation (e.g., emittance)
- 95.5 meas vs 97-98% sim
- Optimal point and patter very different
  - Sensitive to not only the IS output distribution but also space-charge compensation (SCC)

RFQ voltage scan

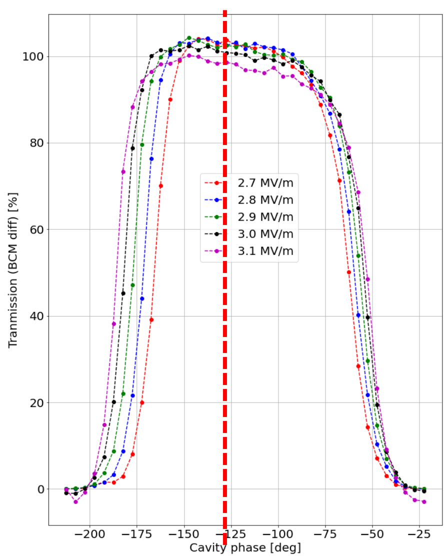


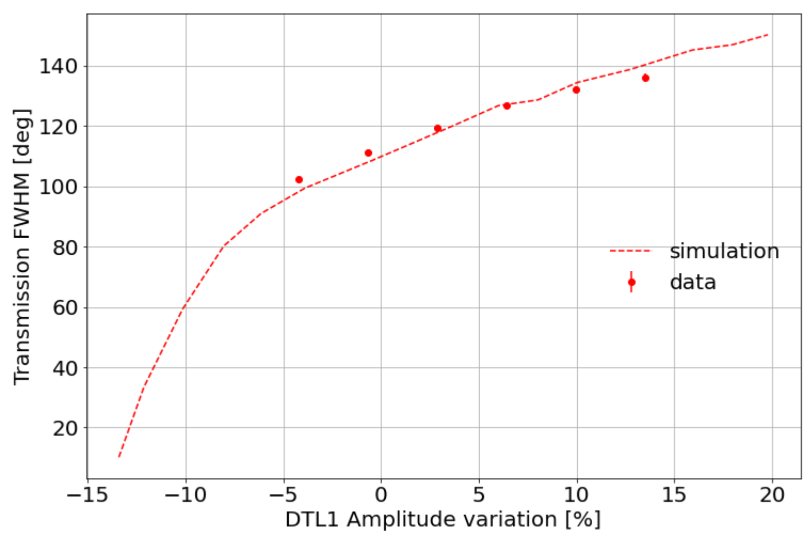
- Voltage is the only degrees of freedom.
- A standard way to make a mode comparison.
- See D. Noll TUPOPA04 for scan with different input conditions.

Cavity amplitude and phase setting
- Major activies during commissioning and start-ups



- Buncher 3 set amp seems off by -10%.
- FWHM of DTL1 transmission scan is insensitive against the initial condition.
- DTL1 set amp seems off by ~5%.
- Further details in Y. Levinsen IBIC22-TUP35.

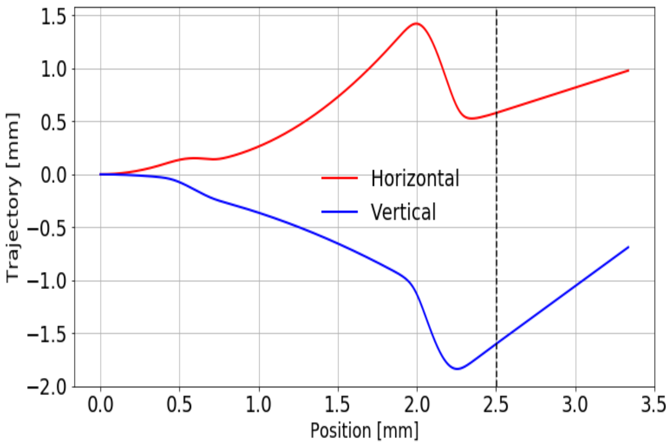




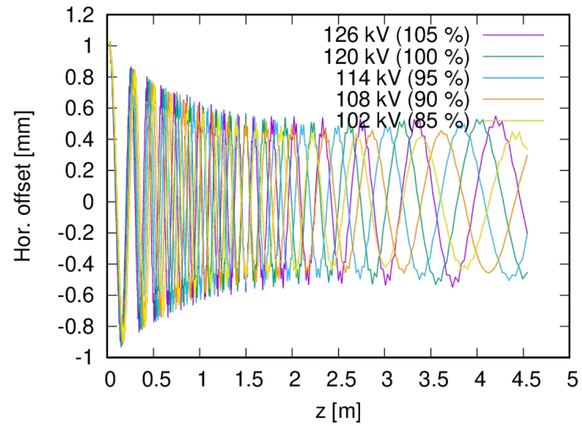
DTL1 transmission vs DTL1 phase

Beam trajectory
Focus on the LEBT so far

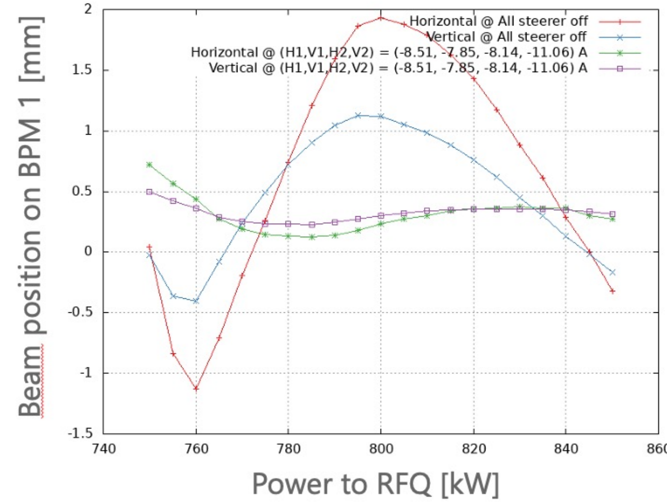
LEBT trajectory with earth magnetic field

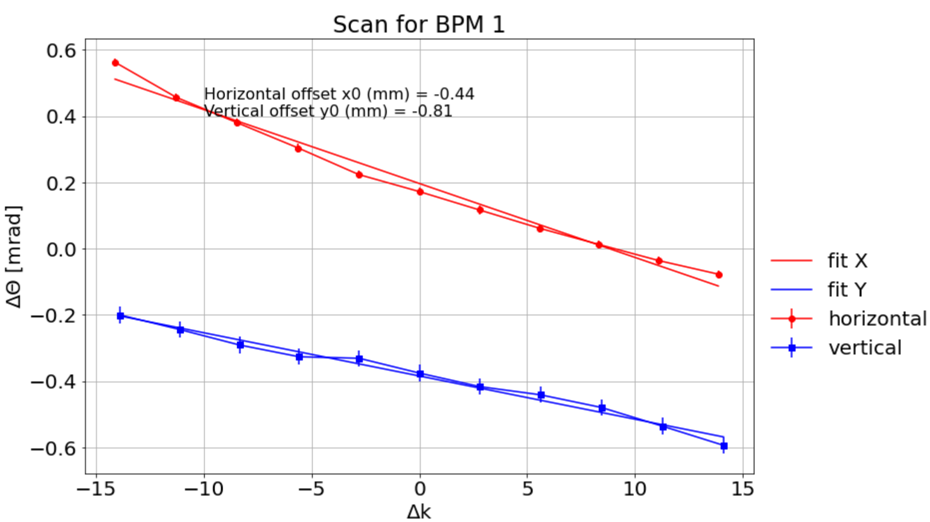


Trajectory modulation with RFQ voltage



Injection correction to RFQ



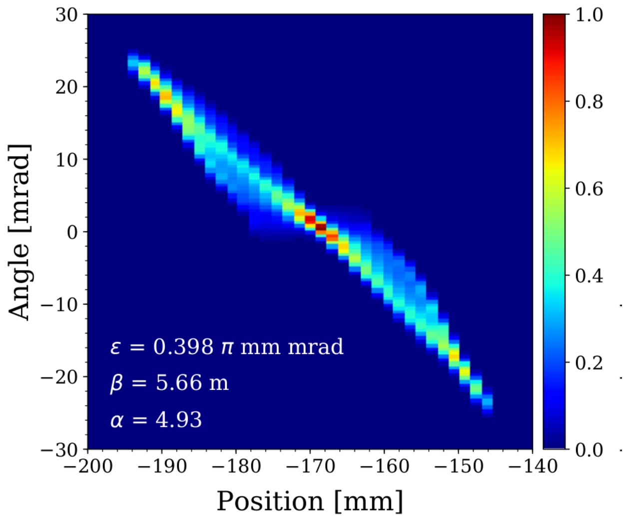


Beam-based alignment example

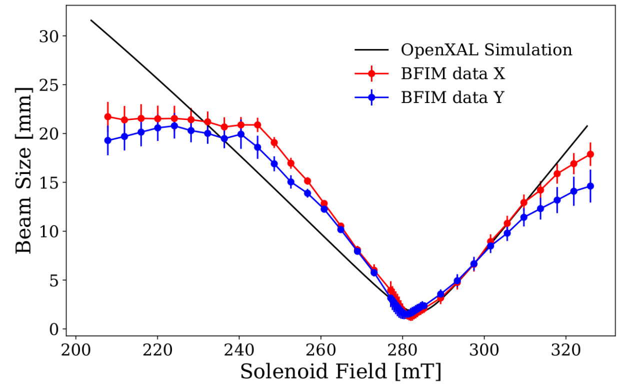
- Earth magnetic field (~47 μT downward) has a large impact in LEBT.
- Injection correction to RFQ for modulated RFQ voltage (also in D. Noll TUPOPA04)
- Not so much attentioned paid to steering in MEBT and DTL1, due to a good transmission.
  - Beam-based alignment tried for MEBT.

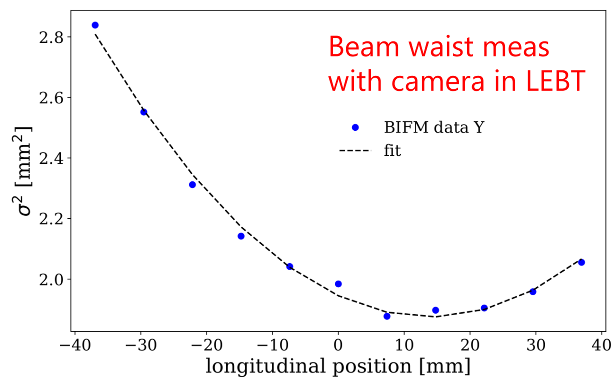
Emittance

LEBT EMU

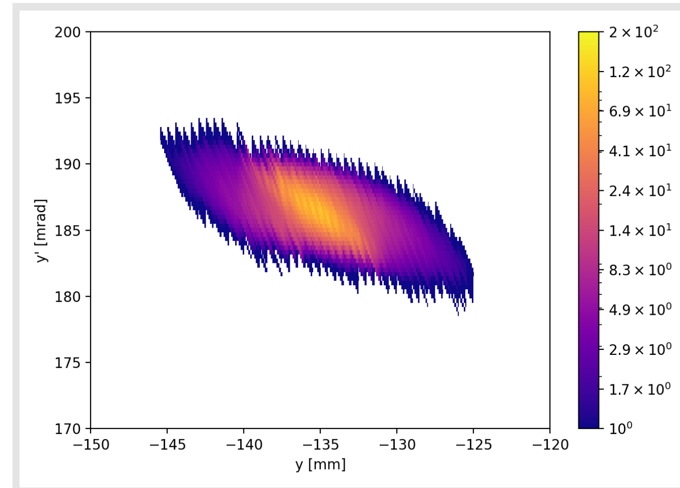


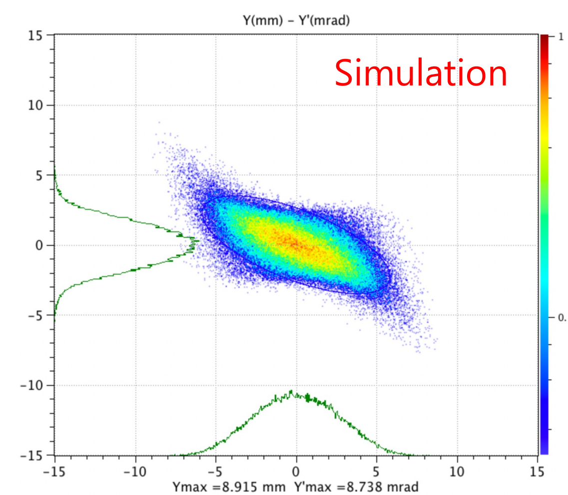
"Quad scan" with cameral in LEBT





MEBT EMU

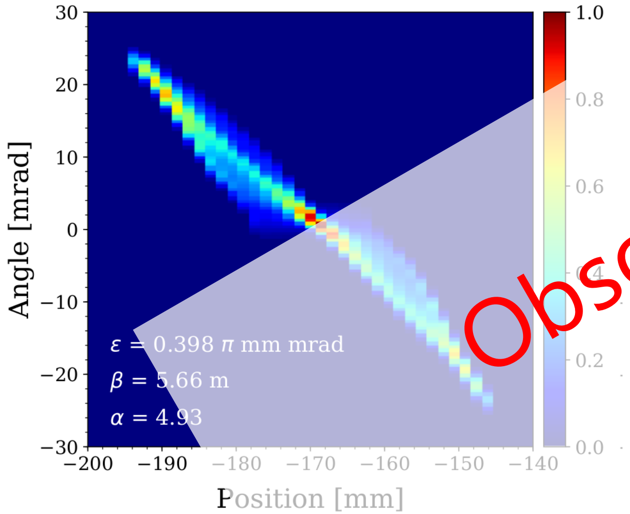




- 3 methods consistent (10-20%) for LEBT.
  - Instruments not available after the IS-LEBT commissioning.
  - Data no longer vaild. (Repeller issue)
- MEBT EMU (V-plane) became available during last ~1 week.
  - Preliminar result shows ~0.5 π mm mrad. (Sensitive to how to cut noise, as usual.)
  - Beta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

Emittance

LEBT EMU



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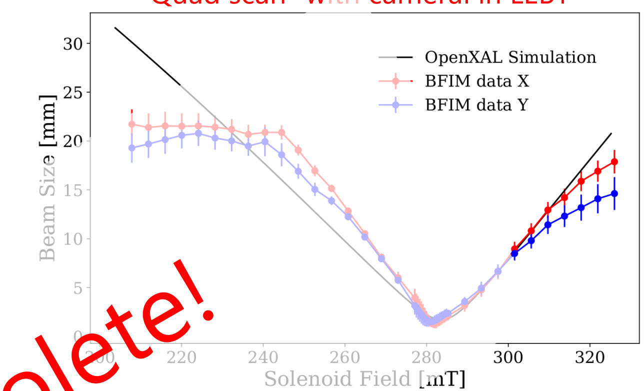
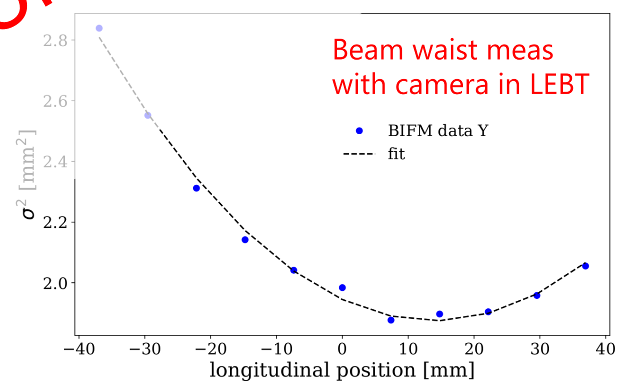
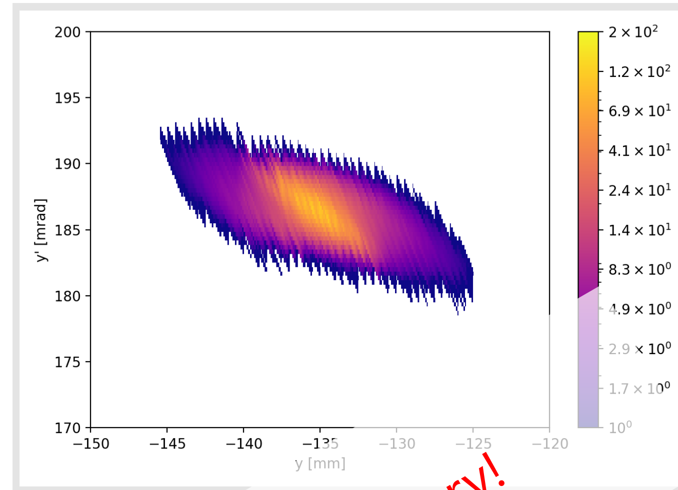
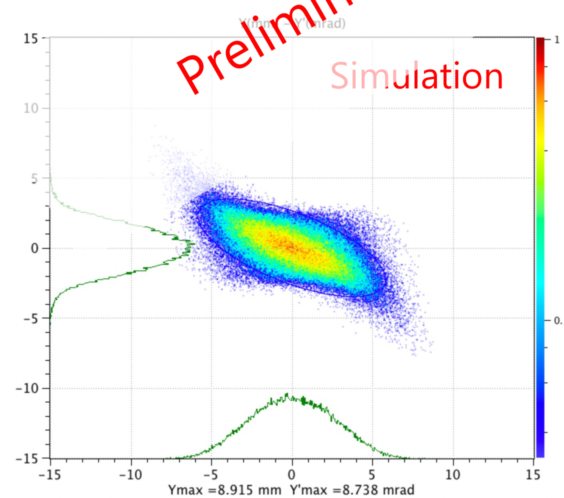




MEBT EMU





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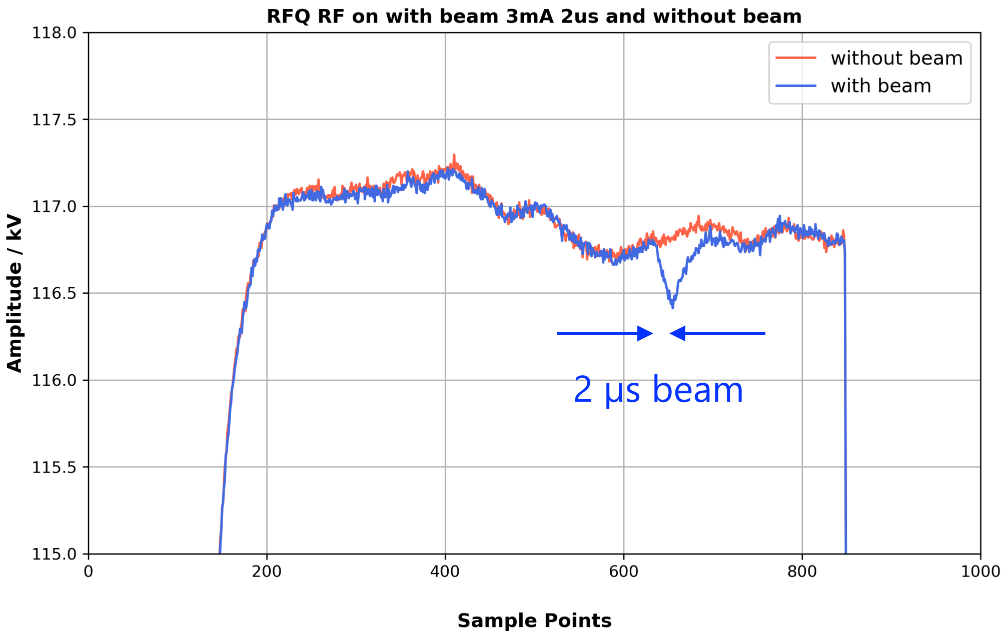
LLRF

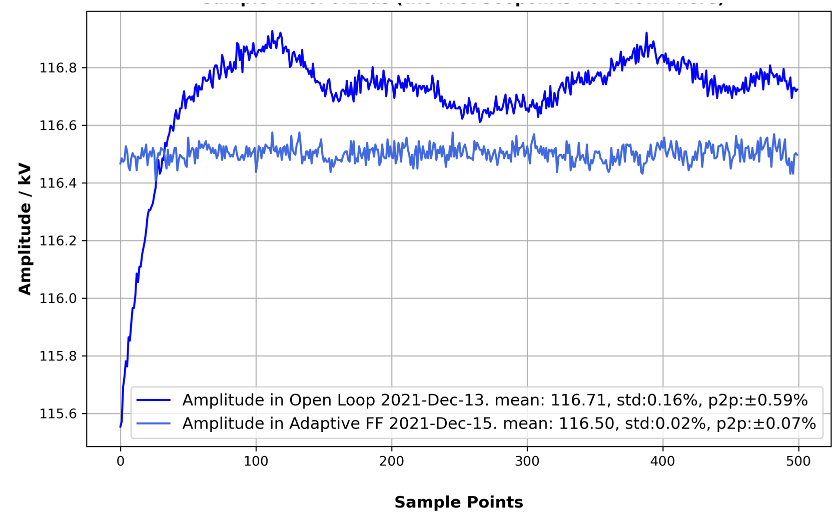
Still under testing but good progress during commissioning

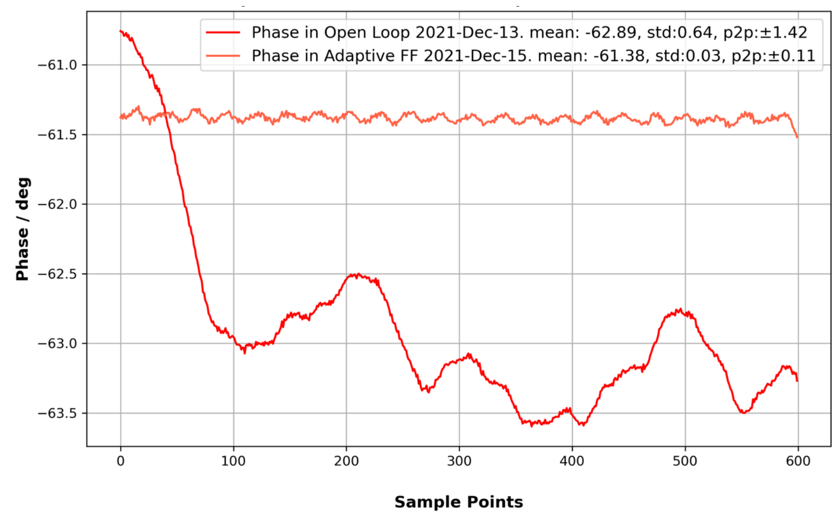
First beam



- 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 ~0.5% for 3 mA and 2 μs beam.

Script based feed-forward





Summary

Summary

- ESS linac project
  - Making steady progress.
  - One commissioning step per year:
    - 2023: Last NCL commissioning step up to DTL4
    - 2024: Beam to the tuning dump
    - 2025: Beam to target
    - 2026: Initial user operations
  - Initial operations will be 800 MeV and 2 MW (capacity).
    - Brightest neutron source with >2 MW. (Thanks to the moderator design.)
- SCL
  - Manufacturing and testing of cavities and cryomodules ongoing.
  - RF installation and testing ongoing.
  - Cryomodules are being delivered to ESS. Installation will start next year.
- NCL
  - RFQ and DTL1 conditioning successfully conducated at the ESS site.
  - Nominal curreent (62.5 mA) beam transported to the DTL1 exit.
    - No issue during curren ramp-up, after fixing the IS repeller issue.
    - **All major hardware (cavities, magnets, …) is good so far. Thanks to in-kinds.**
    - **Pulse length is still limited. Only target can accept beyond 62.5 mA and 50 us steadily.**

EUROPEAN
SPALLATION
SOURCE

Thank you for your attentions!

We look forward to report more progress in the nexgt LINAC!