Status of FRIB Commissioning

Speaker: Peter Ostroumov

F. Casagrande, K. Fukushima, M. Ikegami, T. Kanemura, S. Kim, S. Lidia, G. Machicoane, T. Maruta, D. Morris, A.S. Plastun, J. Popielarski, J. Wei, T. Xu, T. Zhang, Q. Zhao and S. Zhao

MICHIGAN STATE UNIVERSITY

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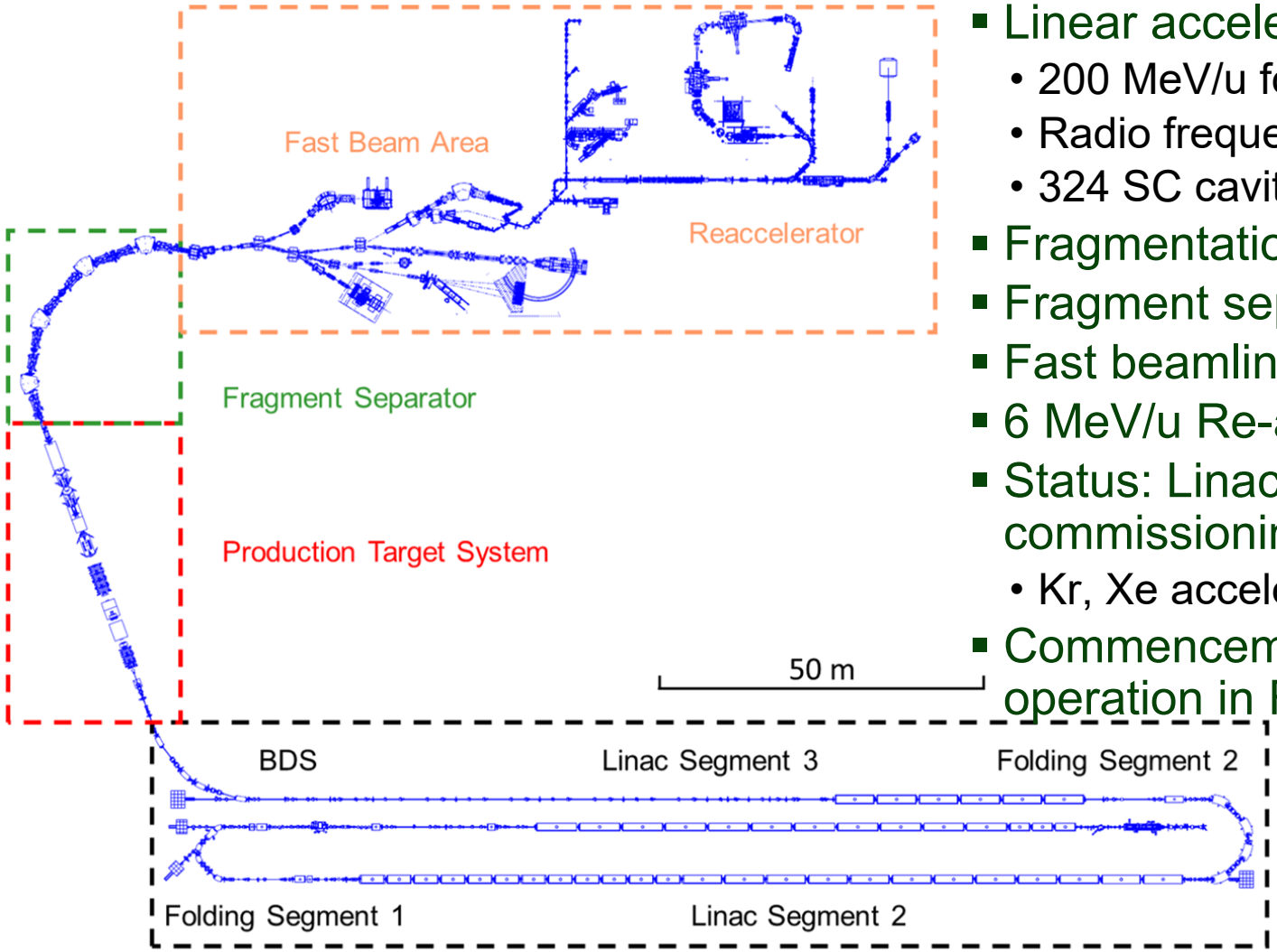
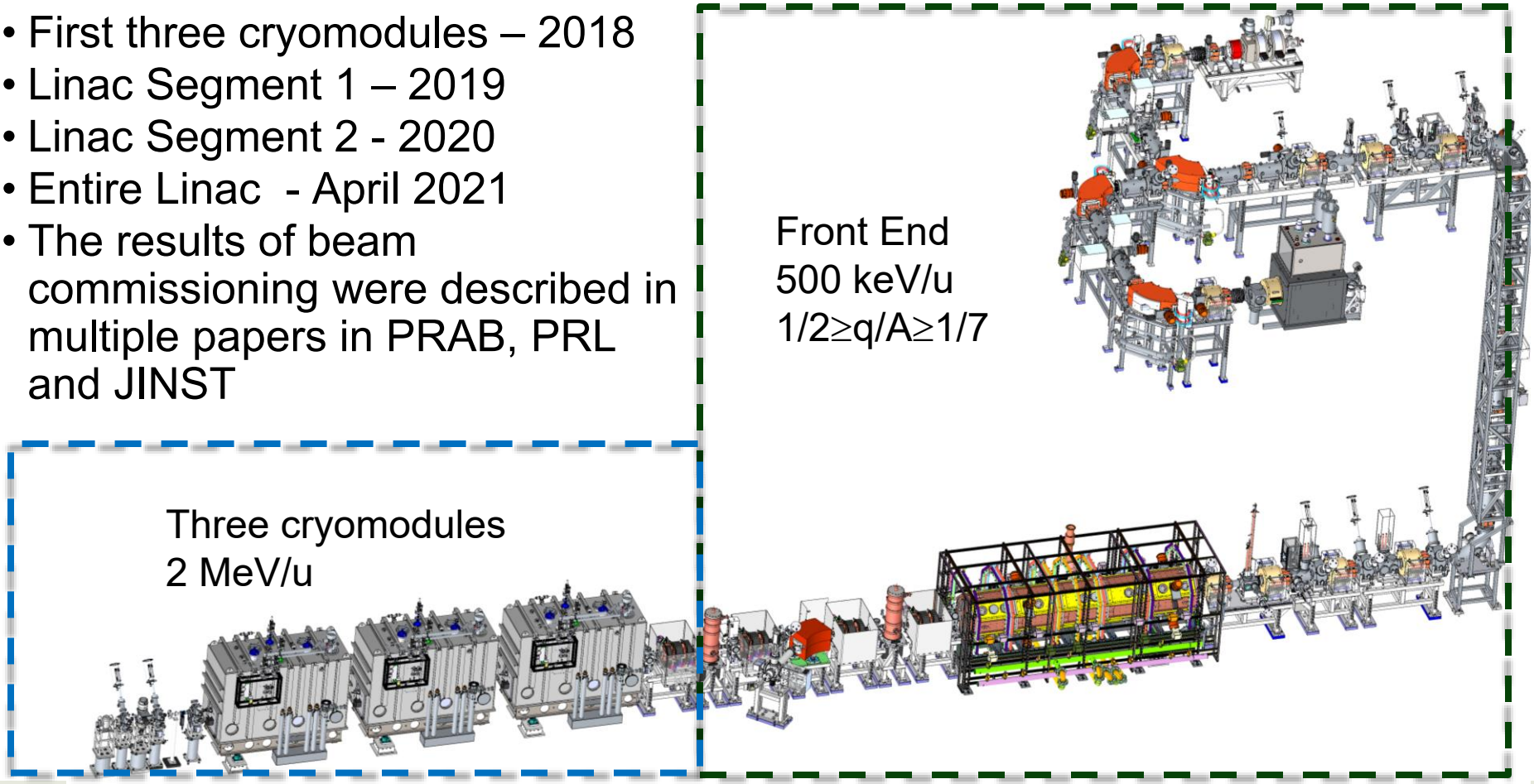
FRIB Layout



- Linear accelerator
  - 200 MeV/u for uranium
  - Radio frequency quadrupole
  - 324 SC cavities in 46 cryomodules
- Fragmentation target
- Fragment separator
- Fast beamlines
- 6 MeV/u Re-accelerator
- Status: Linac construction and commissioning is complete
  - Kr, Xe accelerated to 212 MeV/u
- Commencement of user operation in FY22

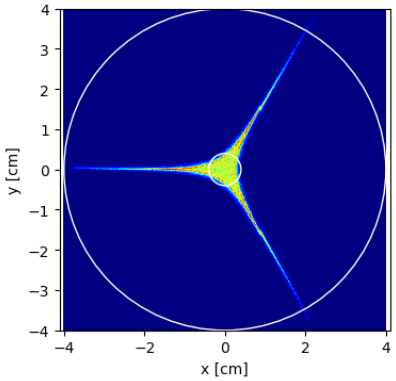
FRIB Linac Beam Commissioning Stages

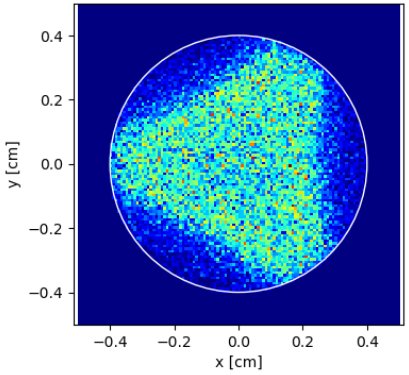
- Beam commissioning
  - Front End – 2017
  - First three cryomodules – 2018
  - Linac Segment 1 – 2019
  - Linac Segment 2 - 2020
  - Entire Linac - April 2021
  - The results of beam commissioning were described in multiple papers in PRAB, PRL and JINST



Simulations and Beam Matching in Upper-LEBT

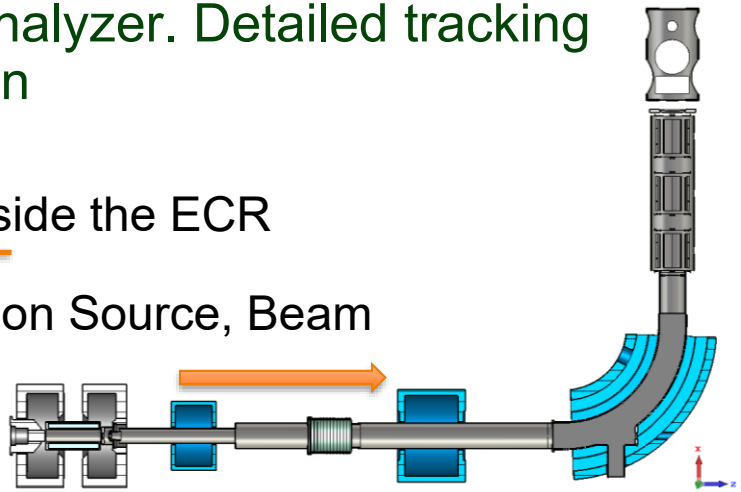
- ECR Ion Source extraction to charge-mass analyzer. Detailed tracking with space charge, multi-ion and neutralization





Tracking inside the ECR

ECR Ion Source, Beam

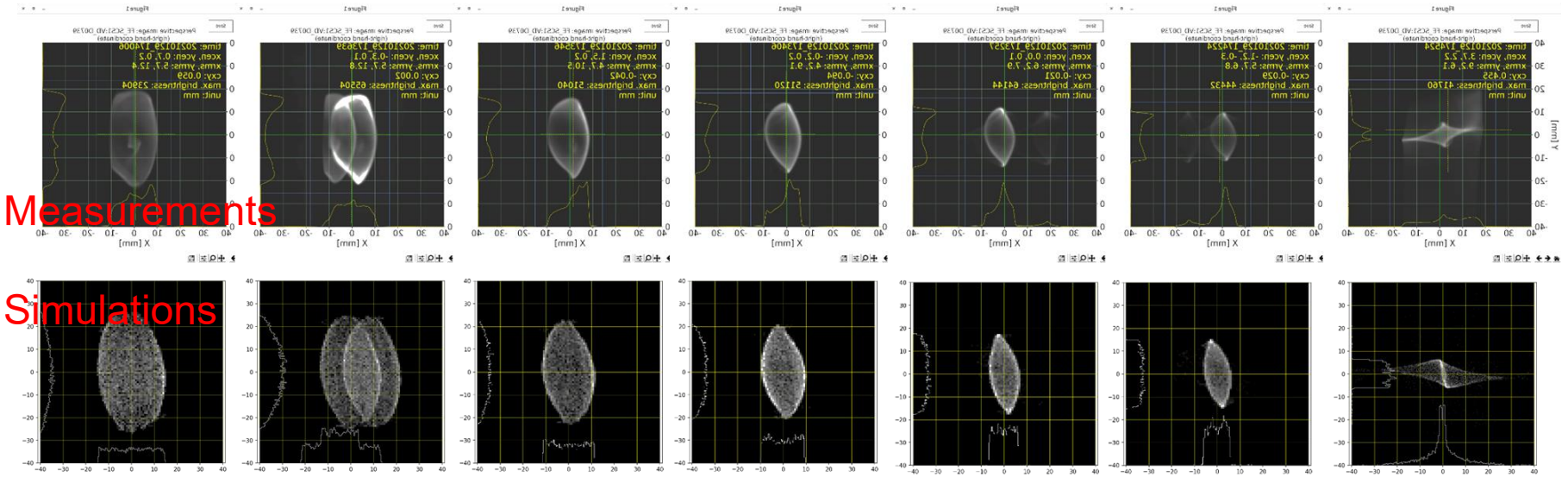


Xenon beam

22+ 23+ 24+ 25+ 26+ 27+ O4+

Measurements

Simulations



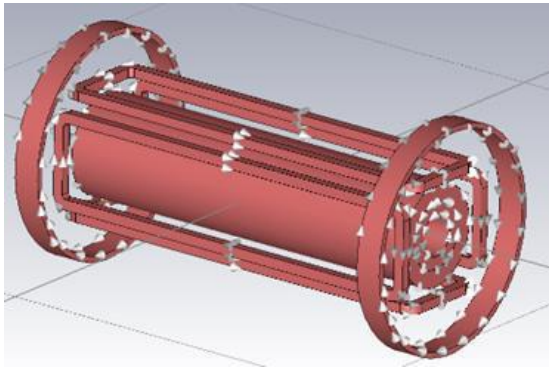
SRF Cryomodules

Example of cryomodules' cold mass

β = 0.53

β = 0.085

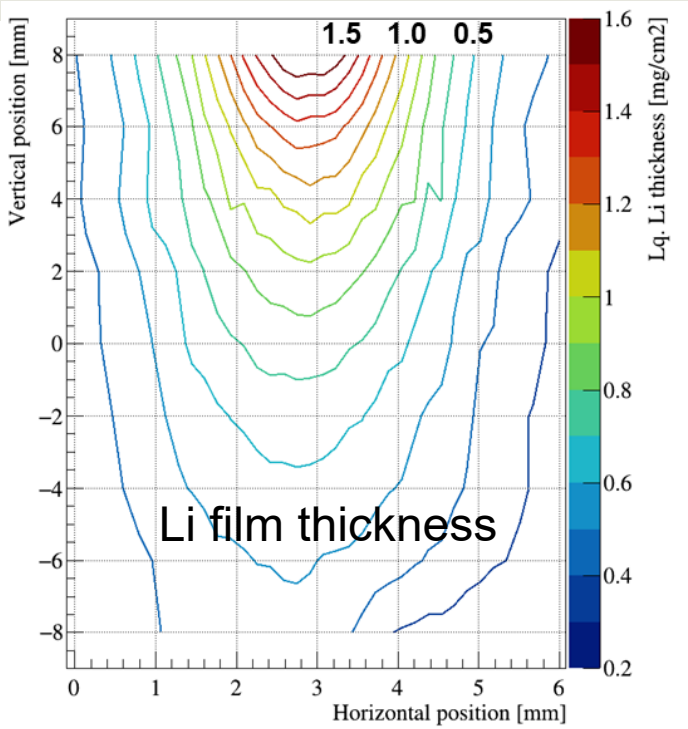
Cryomodules include SC magnet assembly of solenoid and dipole coils

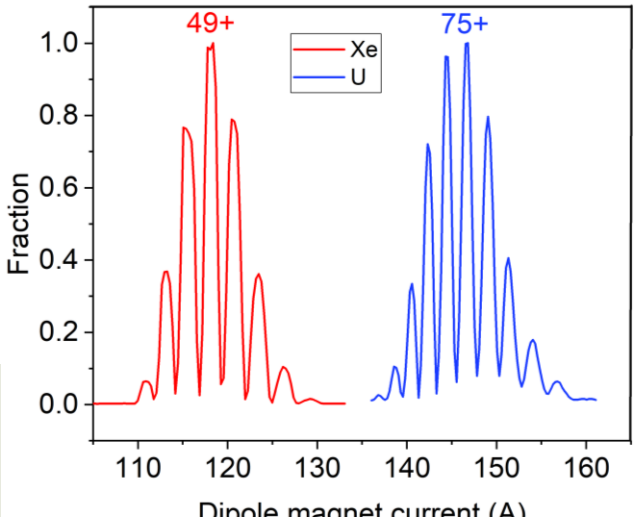


All 46 cryomdules installed in the tunnel

Liquid Lithium Stripper

- Tested with 17 and 20 MeV/u Ar, Xe and U beams
- Tested with 10 pμA pulsed argon beam
  - Average beam power was limited by 500 W beam dump after Linac Segment 1
- The film thickness measured by scanning the film position across the ion beam
  - 1 mg/cm^2 for Xe and Ar beams
  - 1.4 mg/cm^2 for U
- For Xe, Ar, the charge state distribution is consistent with ETACHA4
- Uranium beam charge states are lower than ETACHA4 prediction



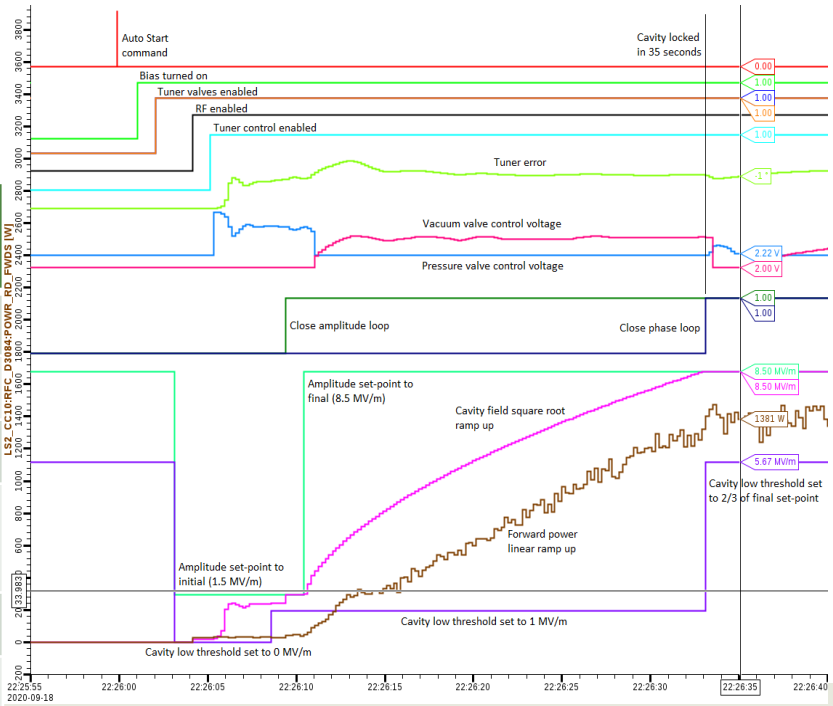


Auto-Start of Resonators

- High accelerator availability through automation
  - Auto-start reduces turn on effort and human error
  - Fast recovery reduces downtime for systems with long start-up time
- Auto-start works for all types of cavities
  - 40 sec to start to full power for a SC cavity
- Turning on 324 cavities in FRIB takes less than 30 minutes
  - Main constrain is a heat removal time by cryogenics

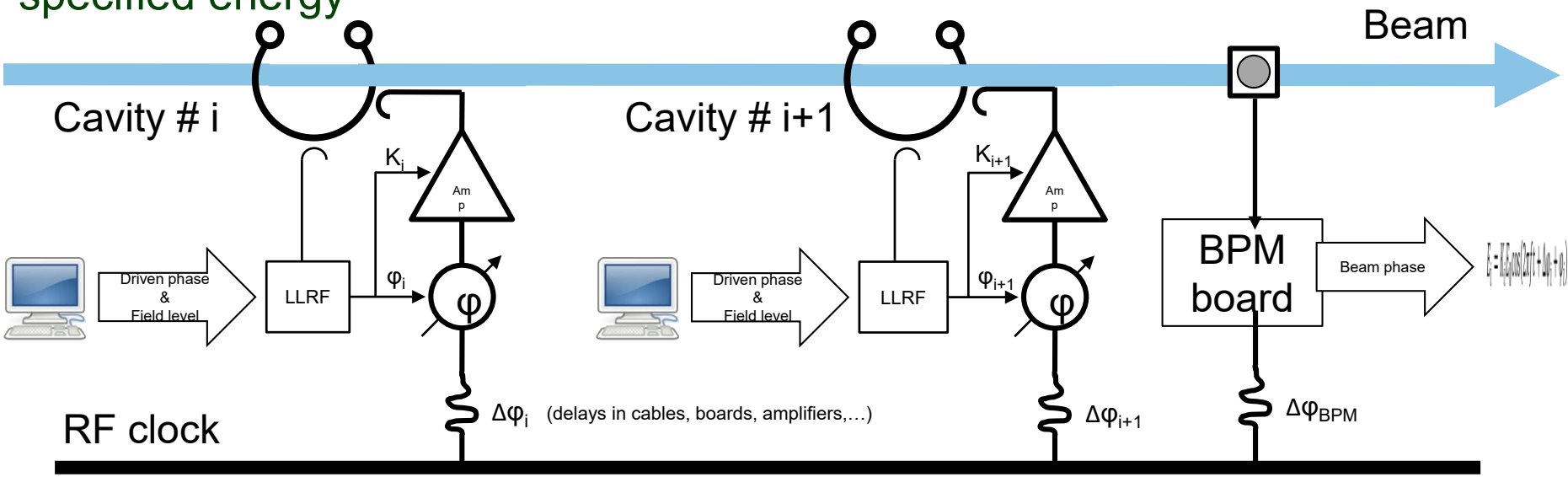
System	Type	Tuner	Start-up Time	Fast Recovery
MHB	RT	N/A	< 30 s	< 30 s
MEBT	RT	2-phase	~ 3 min	< 20 s
MGB	RT	5-phase	~ 10 min	< 20 s
RFQ	RT	water	~ 45 min	ampl 3s phase 30s
QWR	SC	2-phase	< 60 s	N/A
HWR	SC	Pneum.	< 60 s	N/A

Example of HWR Auto-Start



Instant Setting of RF Phases/Amplitudes for Linac Segments

- Static phase shifts in RF transmission/amplifier lines and BPMs' cables were calibrated by the beam of known velocity
- The model calculates phase and amplitude setting for any ion to reach specified energy



Cavity field: $E_i = K_i E_0 \cos(2\pi f t + \Delta\varphi_i + \varphi_i)$

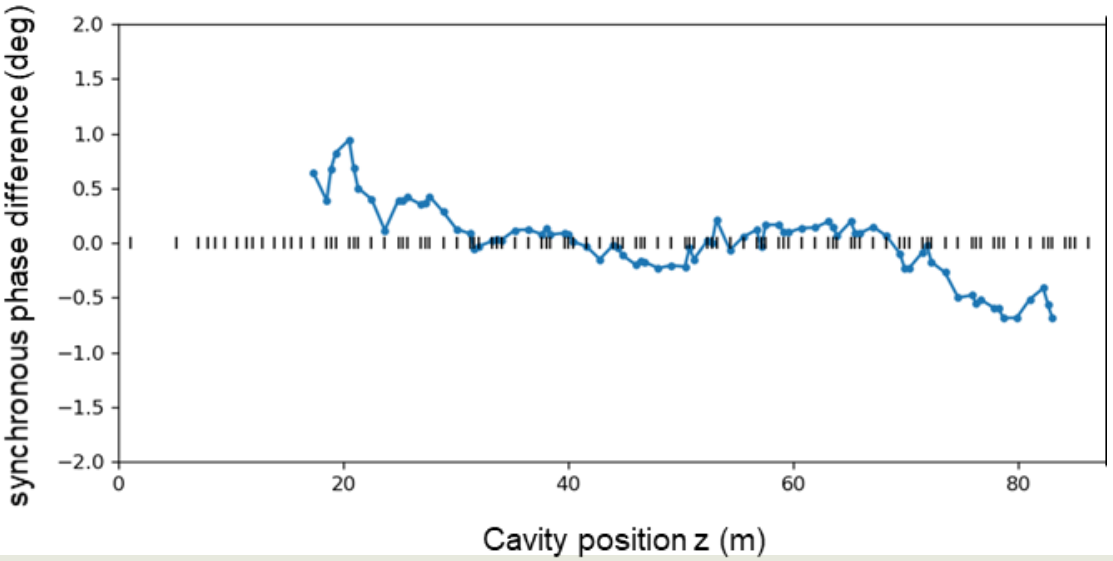
- Model

$$\begin{cases} \dfrac{dW}{dz} = qE_z(z) \\ \dfrac{dt}{dz} = \dfrac{1}{v_z} \end{cases} \qquad E_z(z) = \begin{cases} K_i E_i(z)\cos(\omega t + \Delta\varphi_i + \varphi_i), & z_{i0} < z < z_{ie} \\ 0, & z_{(i-1)e} < z < z_{i0} \end{cases}, i = 0 \div N$$

Instant Phase/Amplitude Setting in Linac Segment 1

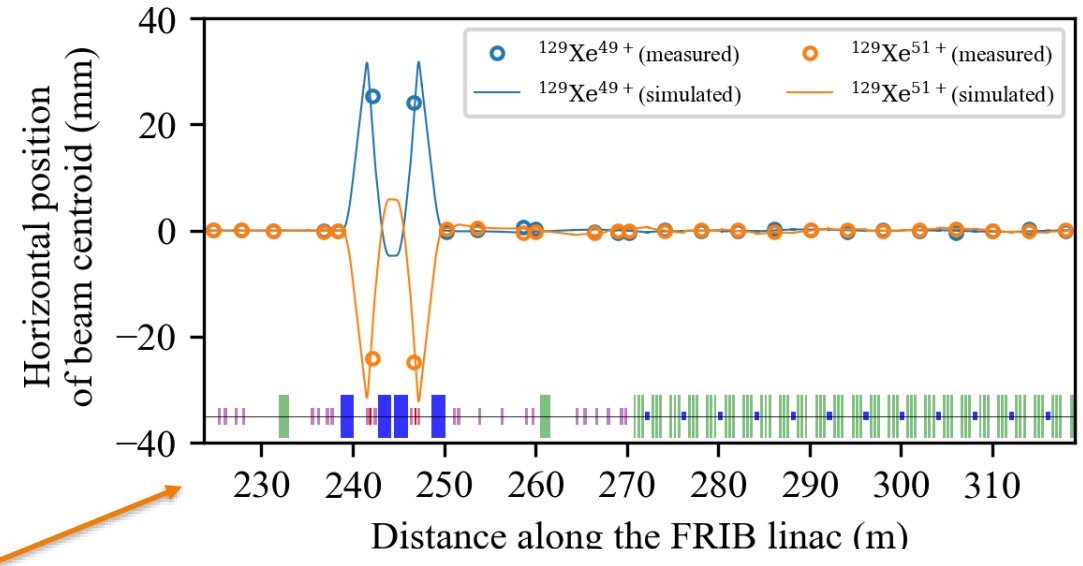
- 100 cavities in Linac Segment 1 were phased using the automated phase-scan application ALPHA to 17 MeV/u $^{86}Kr^{17+}$
  - Phase-scan data was used to create the 1D-computer model of the LS1
- Instant phase/amplitude model-based setting was applied to 88 SC cavities of LS1 to accelerate $^{86}Kr^{17+}$ to 20 MeV/u
- Phase-scan application ALPHA was applied for acceleration to 20 MeV/u
- Compared settings and BPM phases of ALPHA-based and Model-based tunes
  - Both tunes produce the same energy; no change in the transverse phase space
  - The synchronous phase setting was in agreement within less than ±1 deg
- The accuracy of both ALPHA and Model are being improved
- The instant setting will be applied for each FRIB segments sequentially

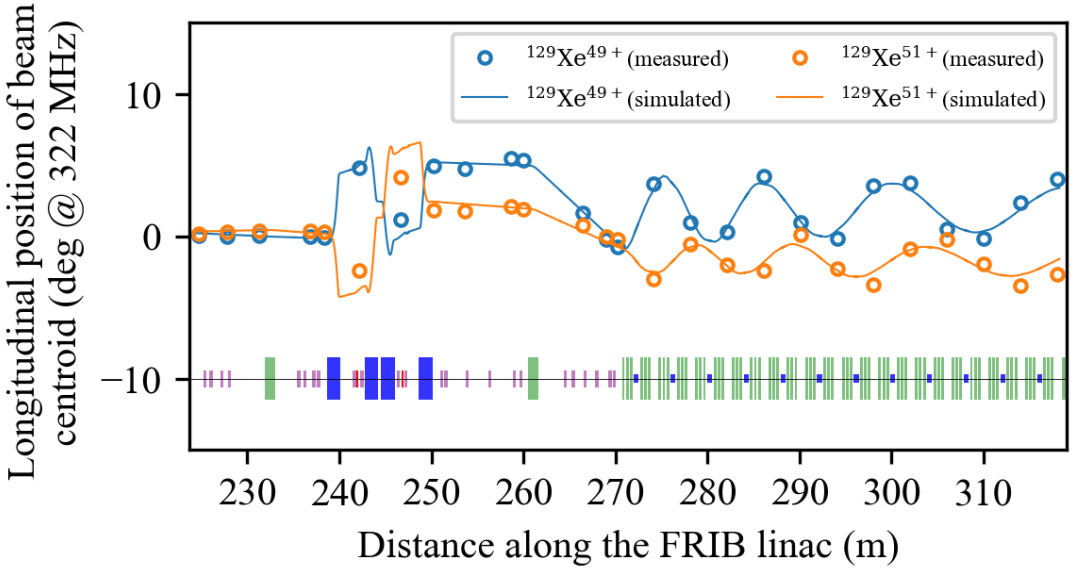
Difference in synchronous phase in LS1



Three Charge States of Xe Accelerated Simultaneously

- Three charge states of Xenon beam from stripper to the end of CC cryomodules
- Factor of 2.5 intensity Increase
- Measured and simulated beam centroids of 51+ and 49+ with respect to 50+
- Transverse
- Longitudinal





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First Simultaneous Acceleration of Multiple Charge States of Heavy Ion Beams in Large-Scale Superconducting Linear Accelerator

P. N. Ostroumov, K. Fukushima, T. Maruta, A. S. Plastun, J. Wei, T. Zhang, and Q. Zhao
Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan 48824, USA

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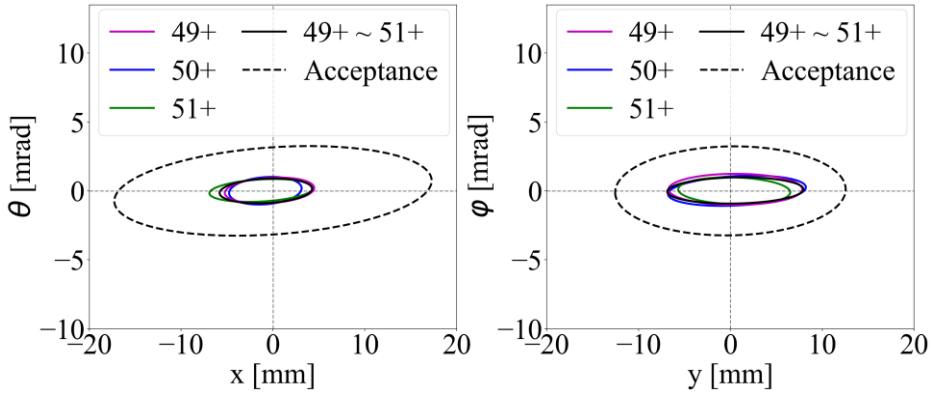
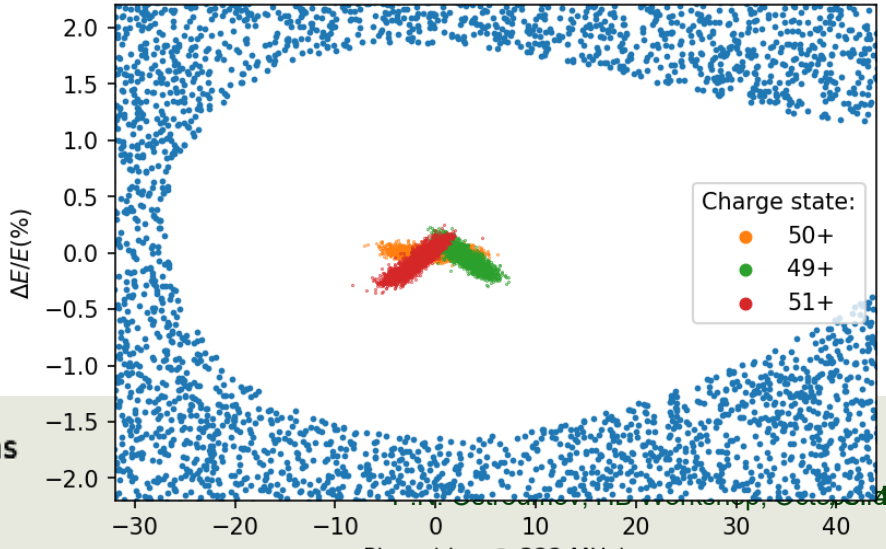
Large Acceptance – Low Beam Losses

- Transverse rms emittances were measured at the end of LS2 for each charge state of Xe
- By the design, the longitudinal emittance is very small to allow multiple charge state acceleration
- The longitudinal dynamics of three-charge-state beam was simulated to the transition from CC to CD cryomoduels in LS2
- Ample of space is available for acceleration of beams with larger emittances
- The linac is ready for acceleration of 400 kW beams

Transverse 10 emittances of three-charge-state Xenon beam and the linac acceptance

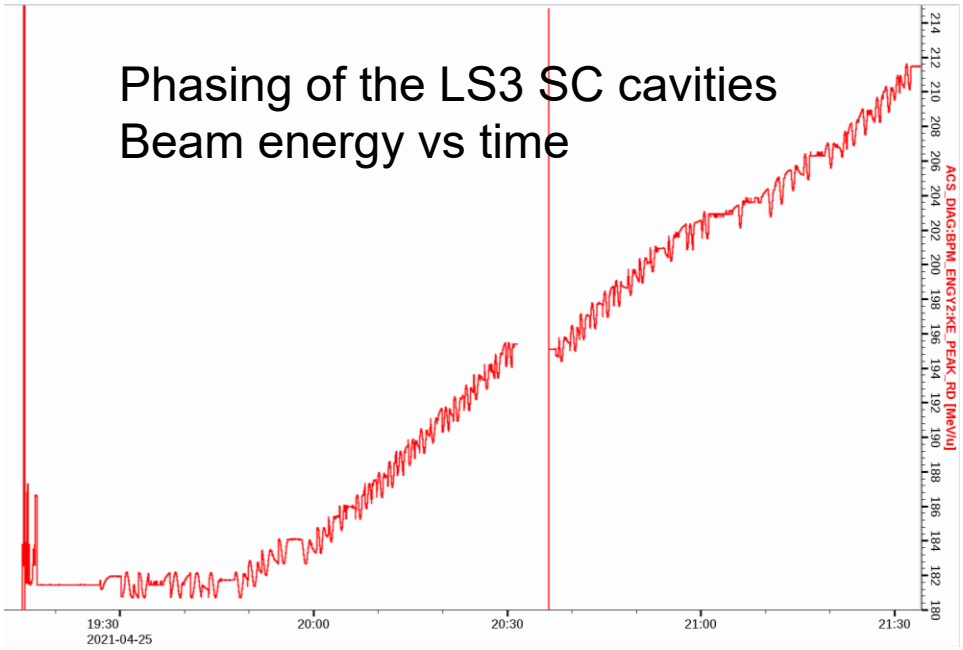


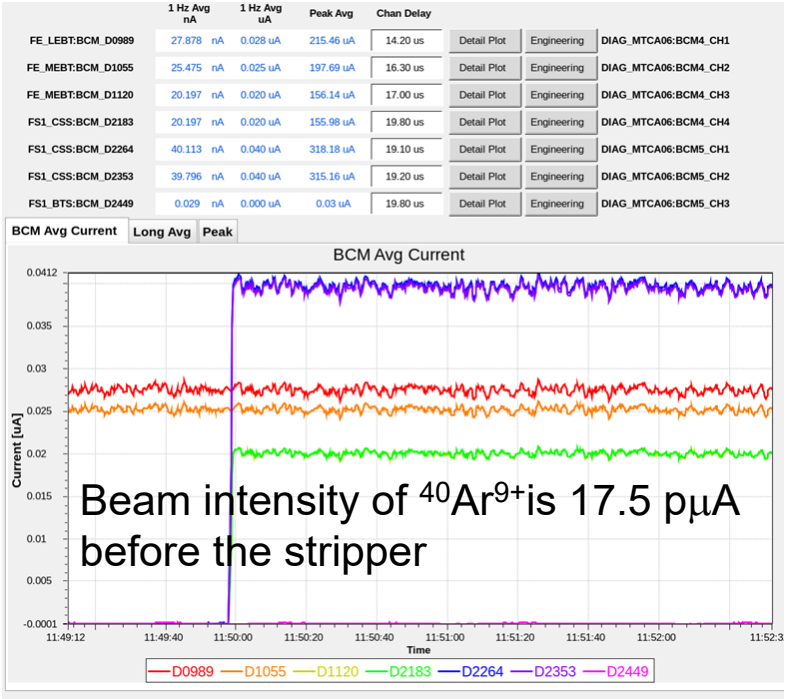
Longitudinal phase space images of three -charge-state Xe and the linac acceptance



Krypton and Xenon Beams Accelerated to 211.5 MeV/u by all 46 Cryomodules

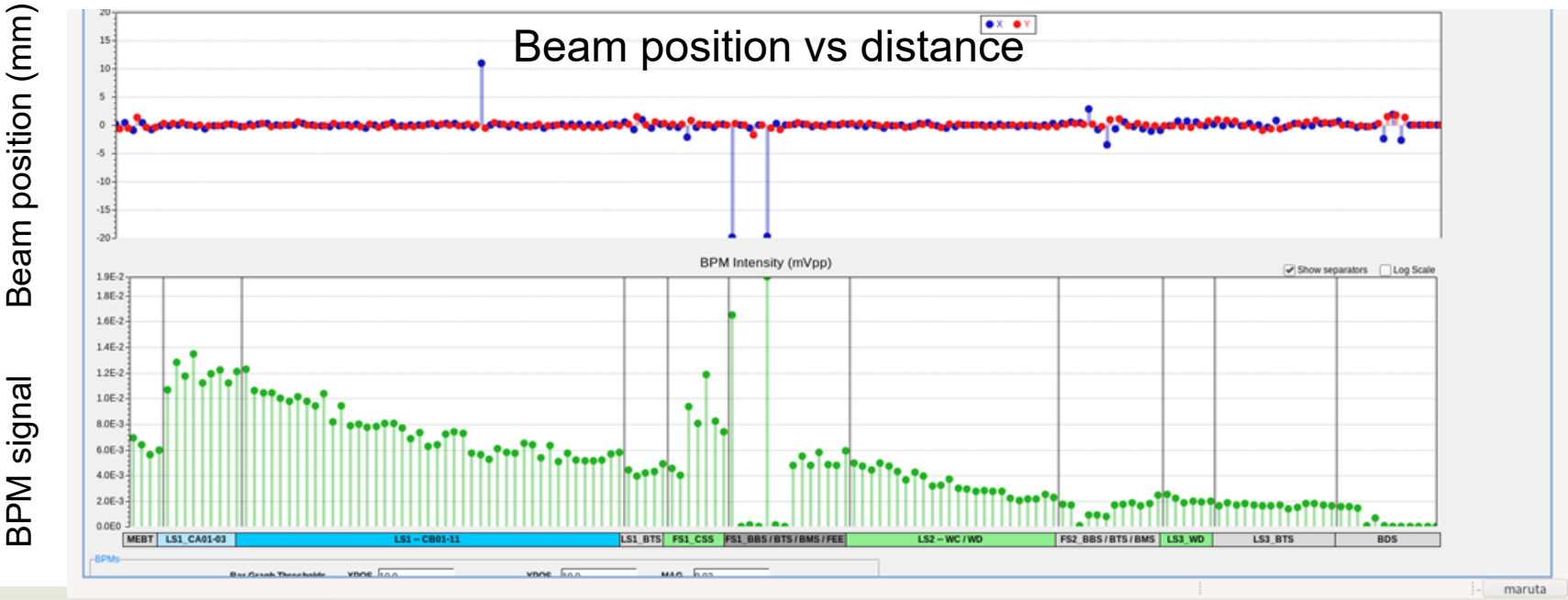
- $^{86}Kr^{34+}$ and $^{124}Xe^{50+}$ beams were accelerated to 211.5 MeV/u with 100% transmission and delivered to the Beam Delivery System (BDS) beam dump both in pulsed (peak current is 1 pμA) and CW modes.
- We demonstrated 200-kW equivalent pulsed Ar beam in LS1 with 100% transmission within the Beam Current Monitor (BCM) measurement errors
- Accelerator availability during the beam commissioning and early operation was 93%





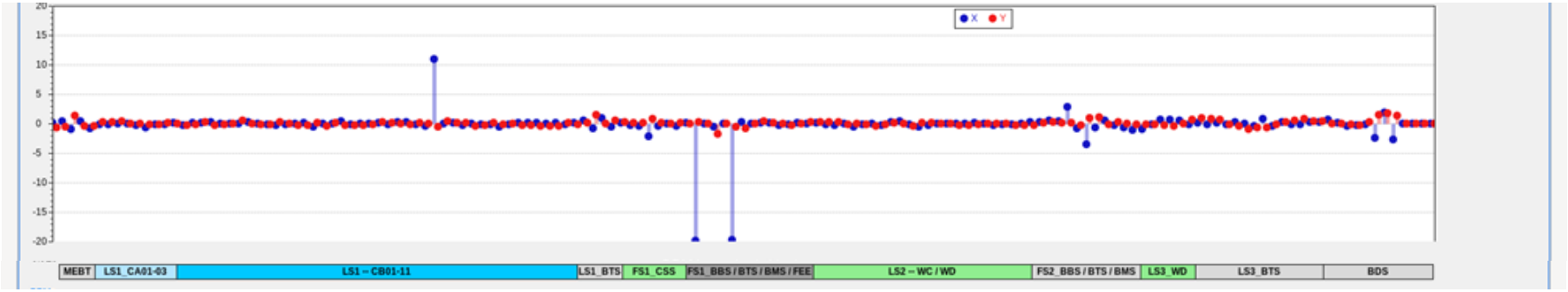
Beam Central Trajectory Correction

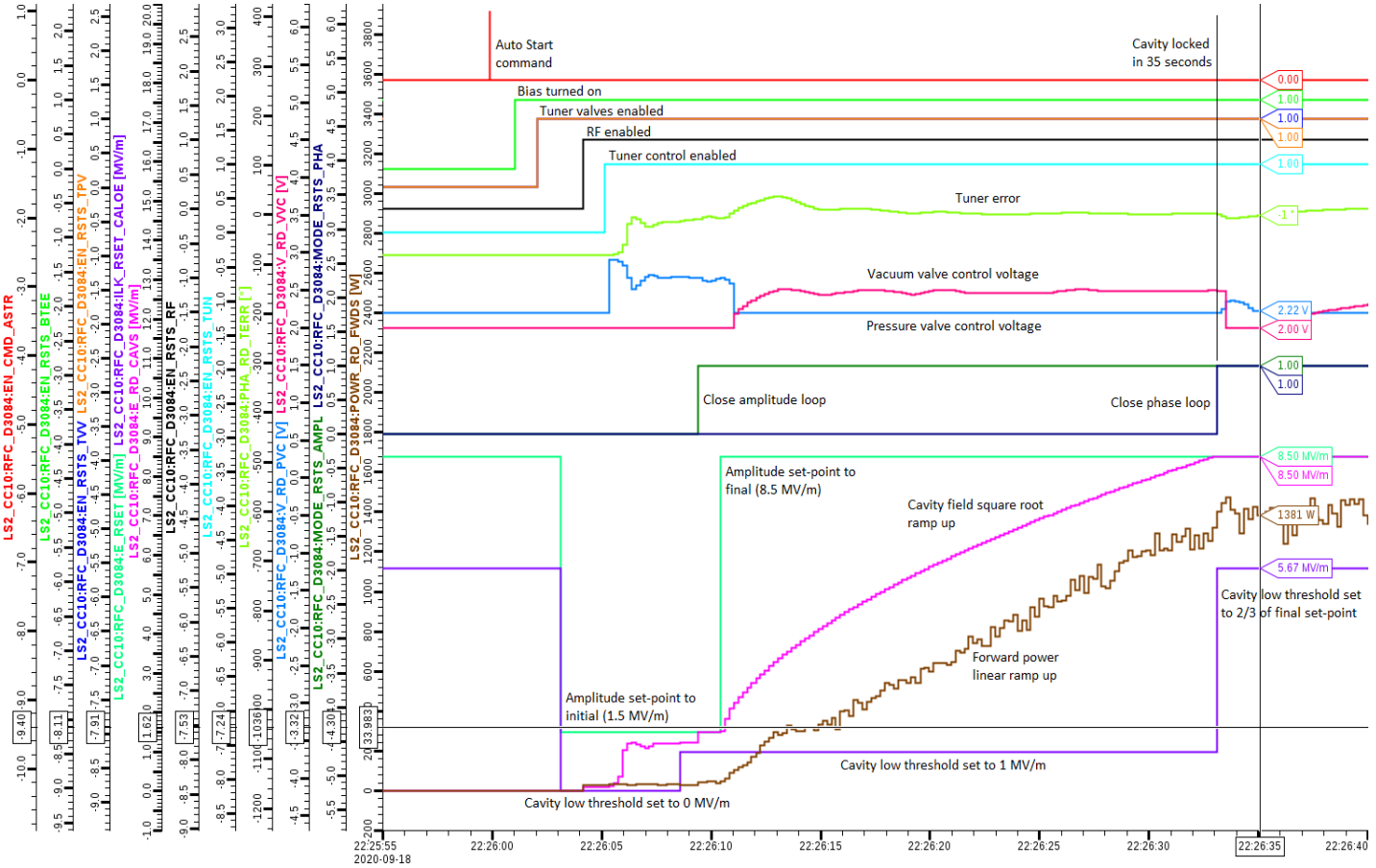
- There are 144 BPMs in the FRIB linac to measure beam positions
  - Renewal frequency is 5 Hz
- High Level Application is based on ORM (Orbit Response Matrix)
  - Response matrix is model based; can be also based on measurements
  - The procedure is applied to ~20 BPM/correctors section by section. Each section tuning time is a couple of minutes



Summary

- FRIB linac beam commissioning is complete
  - Fragment separator will be commissioned in January 2022
- Commencement of user operation is scheduled in early 2022
  - The first Program Advisory Committee (PAC1) approved 34 experiments
  - PAC1 primary ion beams are ^{48}Ca, ^{124}Xe, ^{36}Ar, ^{82}Se, ^{78}Kr, ^{86}Kr, ^{238}U, ^{58}Ni, ^{208}Pb
- Next challenges are
  - Beam power ramp up
    - » Maintain low beam losses in the linac
    - » Control beam losses in the Target Hall and fragment separator
  - Provide isotopes per approved experiments with required intensity, purity and high availability of beam time


X
Y
20
15
10
5
0
-5
-10
-15
-20
MEBT
LS1_CA01-03
LS1 – CB01-11
LS1_BTS
FS1_CSS
FS1_BBS / BTS / BMS / FEE
LS2 – WC / WD
FS2_BBS / BTS / BMS
LS3_WD
LS3_BTS
BDS


Auto Start command
Bias turned on
Tuner valves enabled
RF enabled
Tuner control enabled
Tuner error
Vacuum valve control voltage
Pressure valve control voltage
Close amplitude loop
Close phase loop
Cavity locked in 35 seconds
Amplitude set-point to final (8.5 MV/m)
Cavity field square root ramp up
Forward power linear ramp up
Amplitude set-point to initial (1.5 MV/m)
Cavity low threshold set to 0 MV/m
Cavity low threshold set to 1 MV/m
Cavity low threshold set to 2/3 of final set-point
0.00
1.00
1.00
1.00
1.00
-1
2.22 V
2.00 V
1.00
1.00
8.50 MV/m
8.50 MV/m
1381 W
5.67 MV/m
22:25:55
2020-09-18
22:26:00
22:26:05
22:26:10
22:26:15
22:26:20
22:26:25
22:26:30
22:26:35
22:26:40