FRIB Commissioning

Speaker: Peter Ostroumov

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

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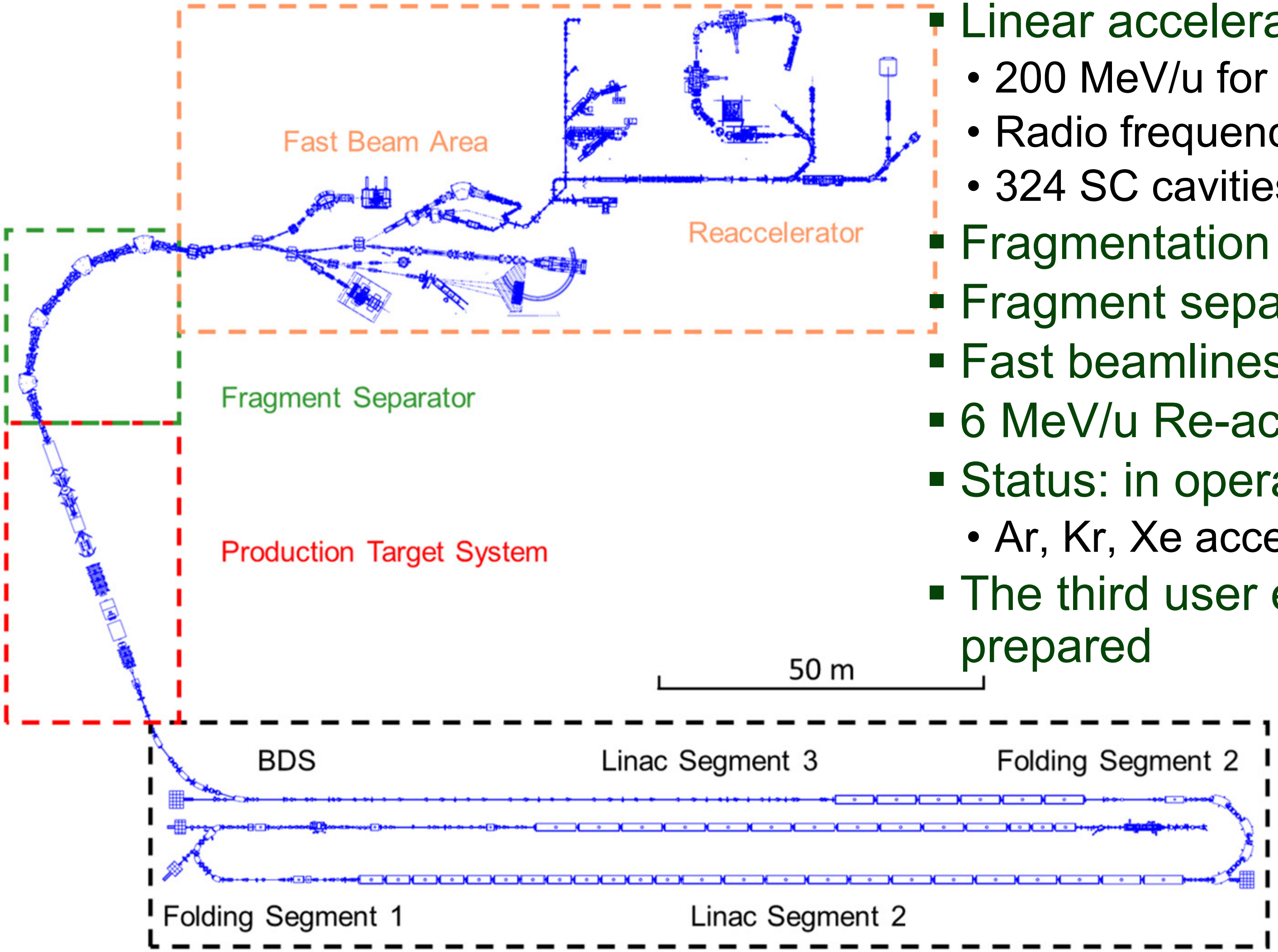
FRIB Layout



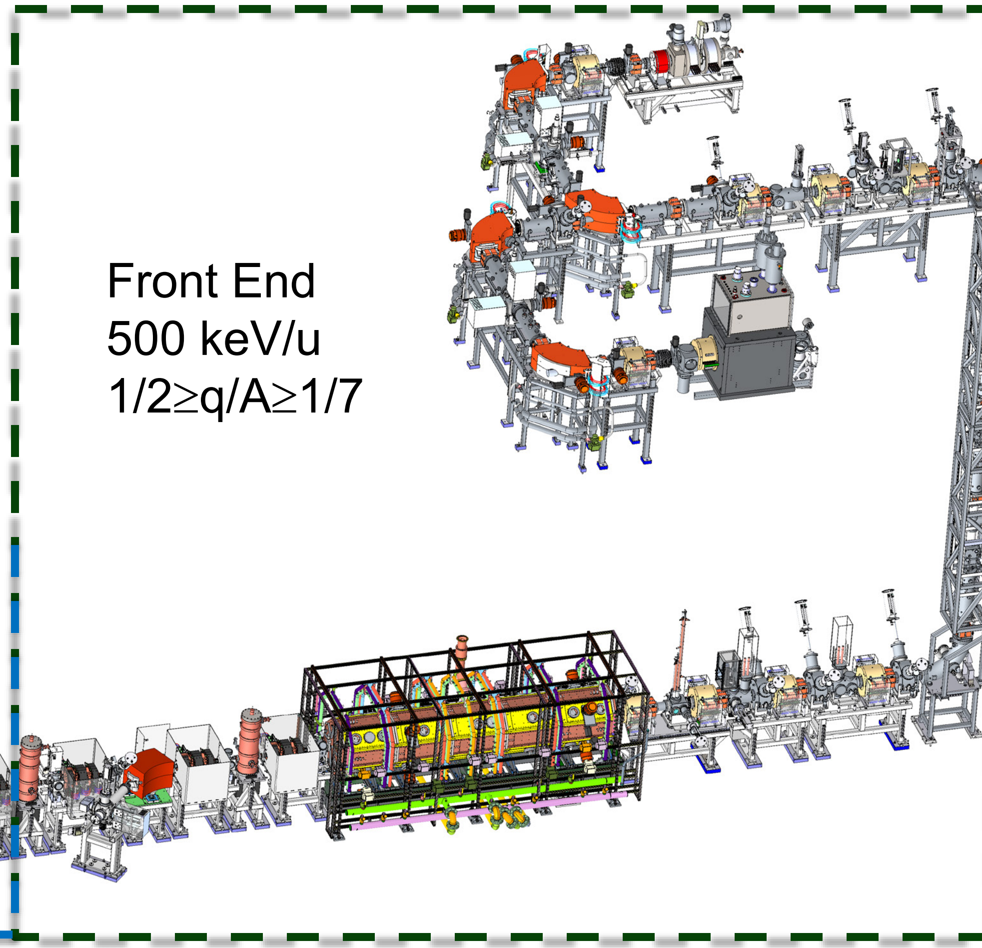
- Linear accelerator
  - 200 MeV/u for uranium
  - Radio frequency quadrupole
  - 324 SC cavities in 46 cryomodules
- Fragmentation target
- Fragment separator
- Fast beamlines
- 6 MeV/u Re-accelerator
- Status: in operation
  - Ar, Kr, Xe accelerated to 212 MeV/u
- The third user experiment is being prepared

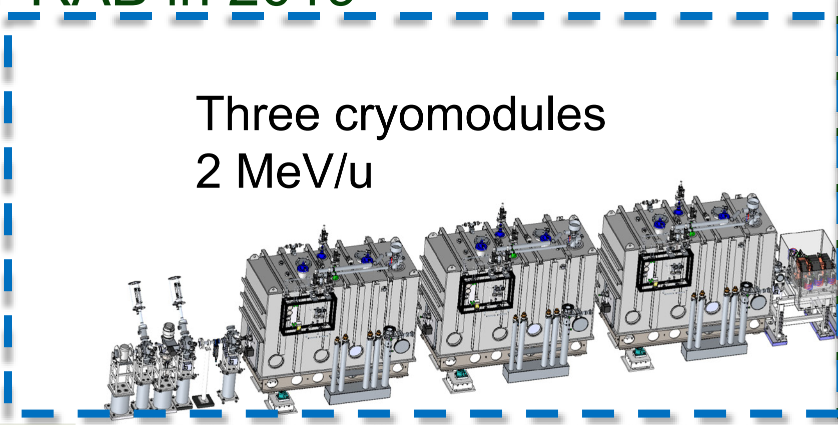
Staged Beam Commissioning

St	Area with beam	Ion species	Beam energy MeV/u	Date	Main goals
1	Front End	Ar, Kr	0.5	July 2017	FE and civil integration
2	First three cryomodules	Ar, Kr	2.2	May 2018	Cryogenic integration, SRF
3	LS1, FS1	Ar, Kr, Xe	20.0	February 2019	104 SRF cavities and stripper
4	FS1, LS2	Ar, Kr, Xe	204 (Ar) 180 (Kr, Xe)	March 2020	2K cryogenics, Linac KPP
5	FS2, LS3	Ar, Kr, Xe	212	April 2021	Linac validation
6	Target Hall	Kr	Rare isotopes	Dec.2021	Project KPP
7	Focal plane of the Advanced Rare Isotope Separator	Ar	210	January 2022	Project completion, readiness for user operation

FRIB Linac Beam Commissioning Stages

- Two ECR ion sources: RT and SC
  - RT- 200 kW of light ions on target
  - SC – up to 400 kW of U
  - Extract and accelerate all ion charge states
- LEBT: transport 2q to RFQ
- CW RFQ
- Beam studies were reported in PRAB in 2019

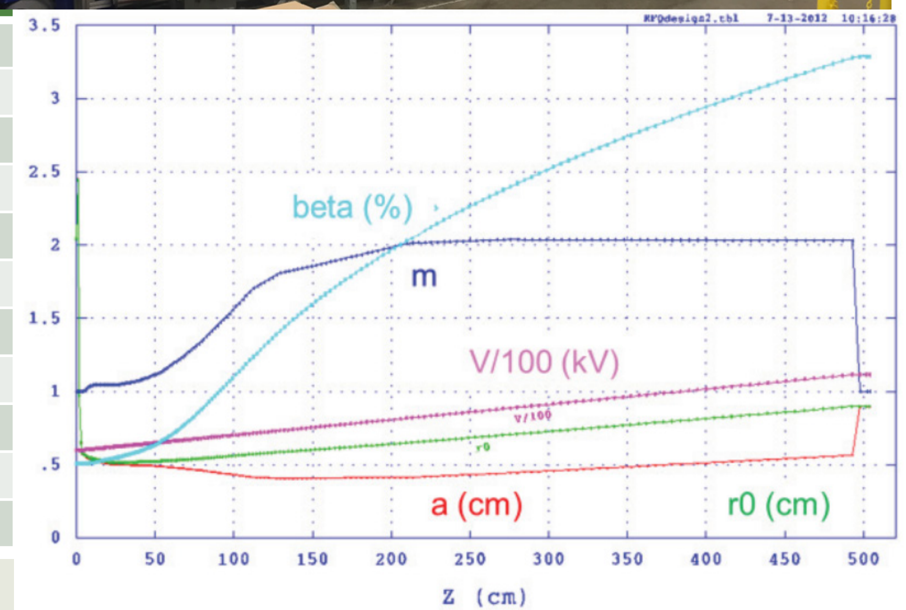




Radio Frequency Quadrupole

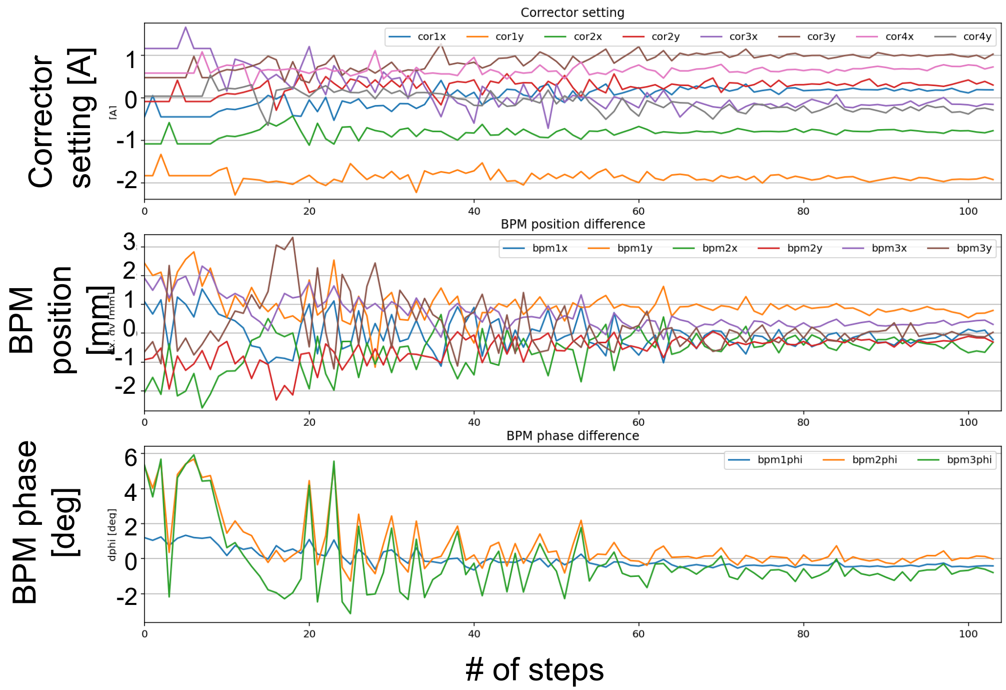
- Unique parameters:
  - CW
  - Maximum voltage is 112 kV
  - Variable R_0 and voltage
  - q/A=1/7
- Conditioned at the design voltage
  - Tested with uranium beam

Frequency (MHz)	**80.5**
Injection/Output energy (keV/u)	12/500
Beam current (typical, µA)	450
Beam emittance (full, norm, πµm)	1.0
Long. Emittance (99.9%, keV/u-ns)	1.5
Transmission efficiency (typical, %)	80
Design charge-to-mass ratio	1/7-1/3
Accelerating voltage ramp (U, kV)	60 – 112
Surface electric field (Kilpatrick)	1.634 (CST)
Quality factor	16500
Operational RF power (kW, O-U)	15 – 100
Length (m)	5.0



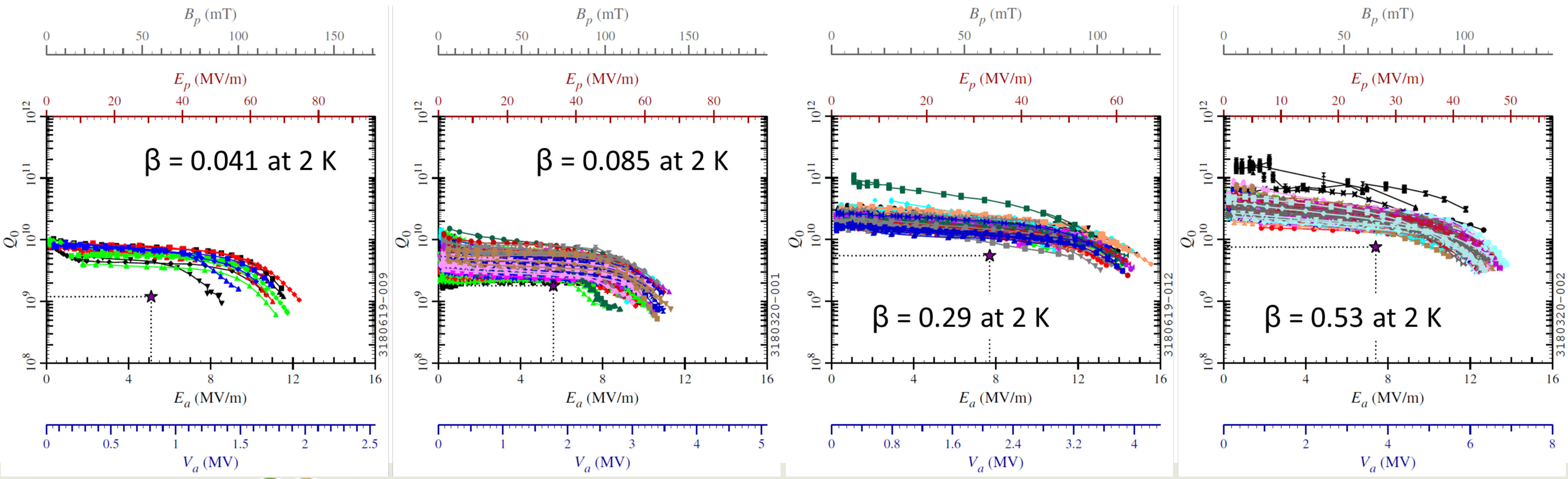
Beam Bunch 6D Vector Matching to SC linac

- A significant beam centroid (6D vector) deviation from previously saved setting has been observed in the MEBT after a cold start of ECR ion source
  - A few mm position and a few degrees of phase deviations in MEBT BPMs
- The python3-based script was developed to fit BPM readings to the previous operation
- Four correctors in LEBT are automatically tuned by Nelder-Mead minimization algorithm
- BPM positions and phase are tuned within +/-1 mm and +/-1 degree
  - About 20 minutes to tune
- Studies are underway to replace the Nelder-Mead with ML-based algorithm
  - Bayesian optimization using experimental data
  - Neural Network based optimization



Superconducting RF

- Challenge: mass-production of 324 SC resonators and 46 cryomodules with required accelerating gradients and specified limit of the heat load
  - This task was successfully accomplished
- FRIB cavity specifications are modest: $E_{PEAK} \cong 30$ MV/m, $B_{PEAK} \cong 60$ mT
  - All cavities exceeded the specifications
  - About 10% higher accelerating gradients are available from the majority of cavities



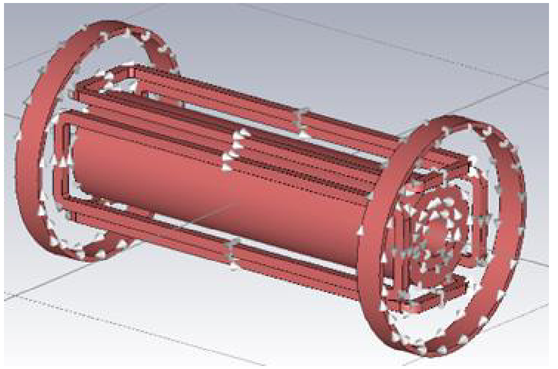
SRF Cryomodules

Example of cryomodules' cold mass

$\beta = 0.53$

$\beta = 0.085$

Cryomodules include SC magnet assembly of solenoid and dipole coils



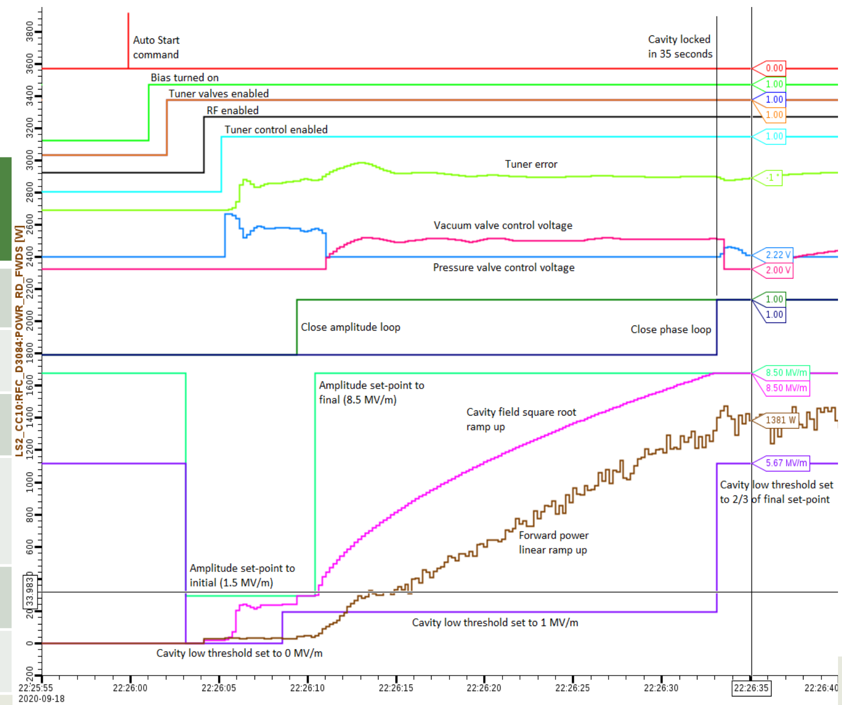
All 46 cryomdules installed in the tunnel and are being used for beam acceleration

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

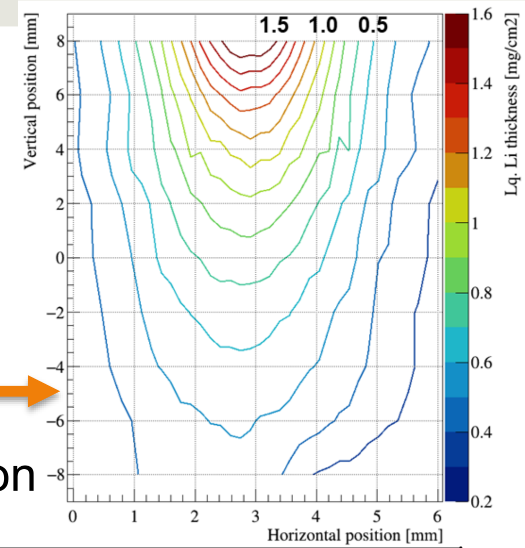
Example of HWR Auto-Start



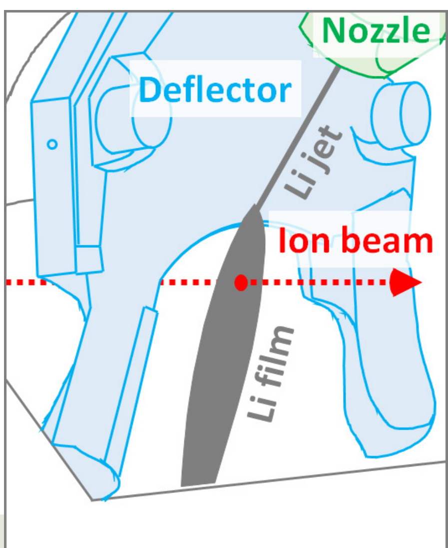
Liquid Lithium Charge Stripper Tested with Ar, Xe and U beams

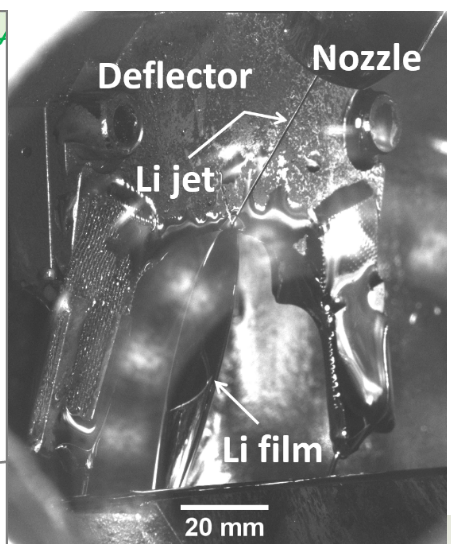
- Tested with 17 and 20 MeV/u Ar, Xe and U beams
- Tested with 10 pμA pulsed argon beam
  - Average beam power was limited by 500 W beam dump
- The film thickness
  - 1 mg/cm^2 for Xe and Ar beams
  - 1.4 mg/cm^2 for U
- Operated 24/7 for user experiment
  - Primary beam was ^{48}Ca

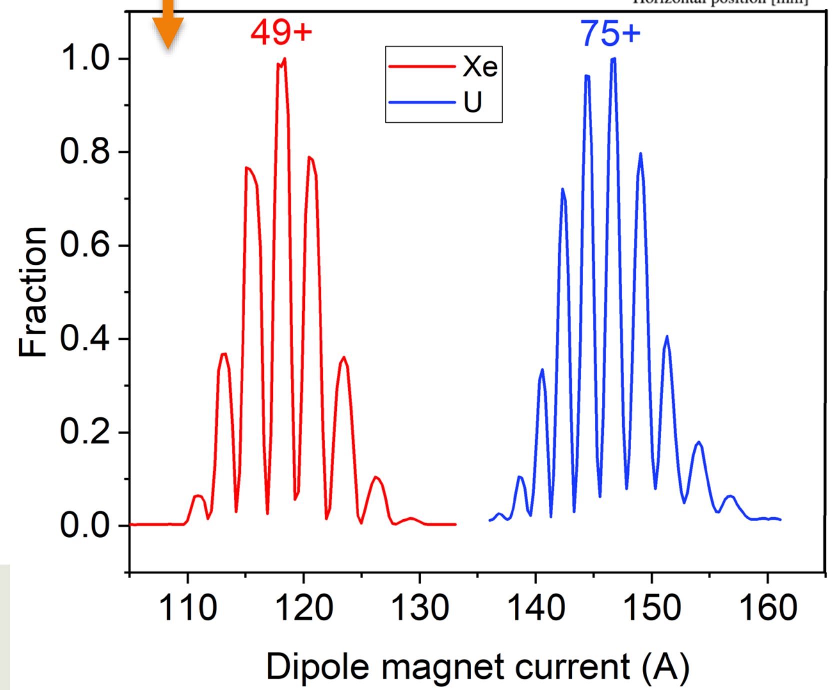
Li film thickness



Charge distribution

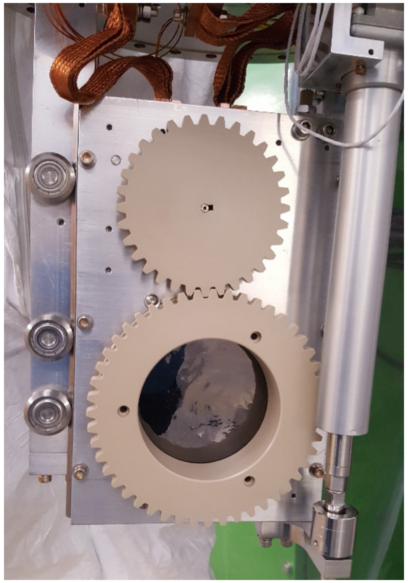


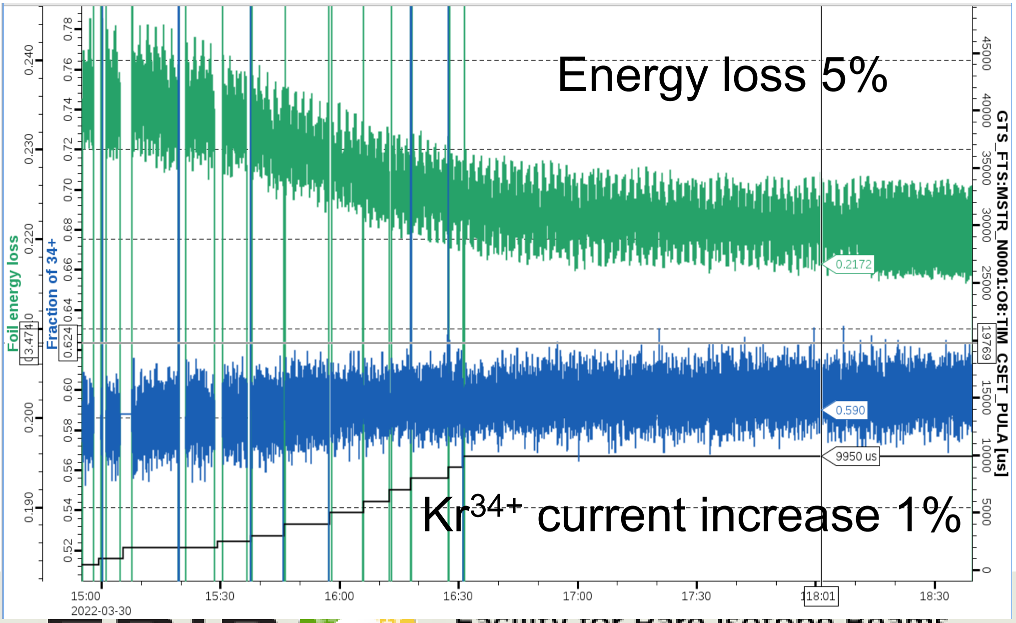


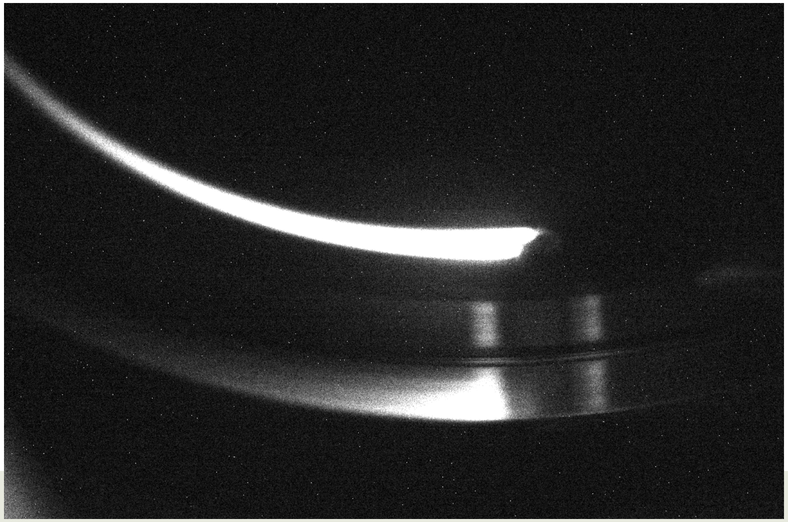


Rotating Carbon Foil up to 10 kW Beam on Target

- Use rotatable carbon stripper for simplicity of operation during the first year
  - 100 mm diameter foil, rotating and up-down motion
- Tested with 440 W ^{86}Kr beam on the stripper
  - Foil thinning is observed
  - Lifetime is sufficient for a single experiment
- Routinely used to run user experiment with ^{82}Se



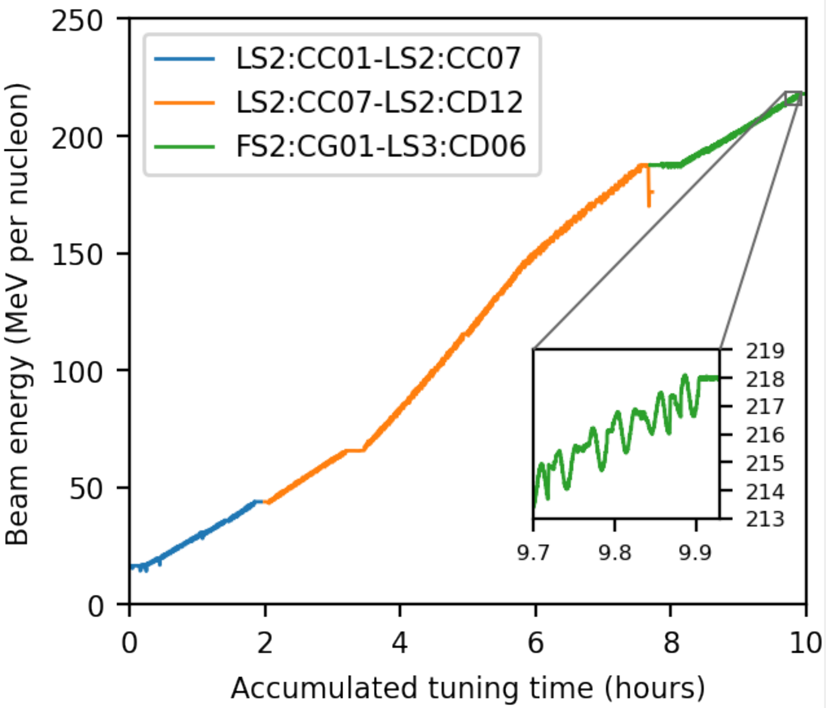




^{36}Ar, ^{86}Kr and ^{129}Xe Accelerated above 200 MeV/u

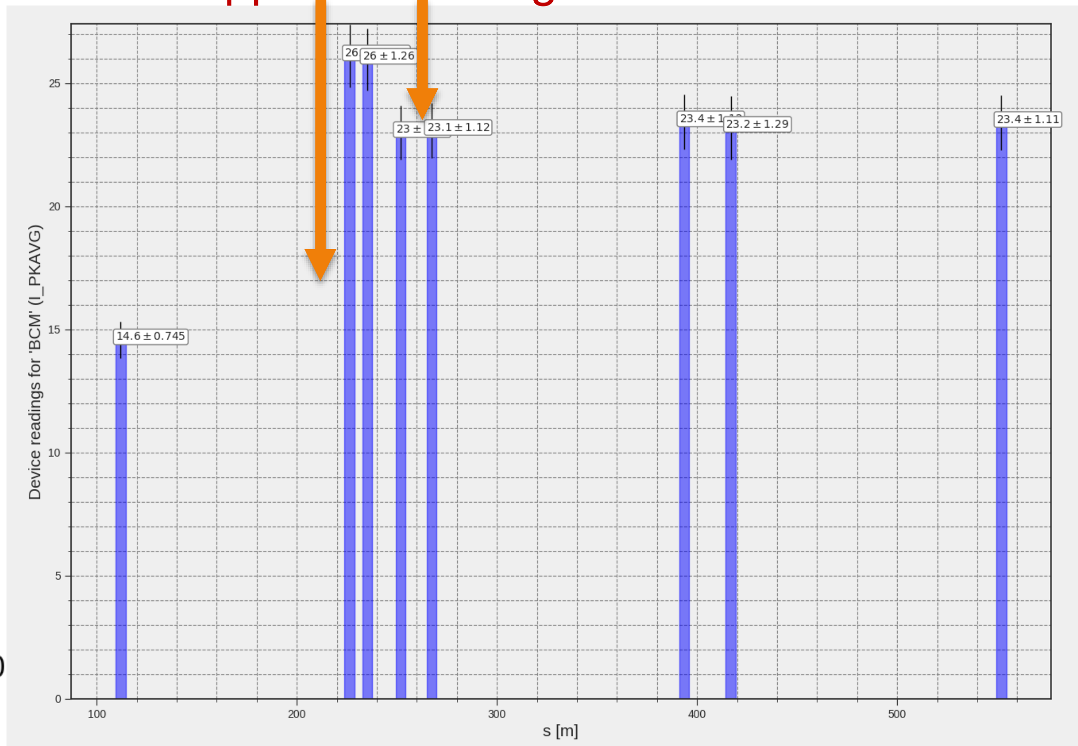
- Three-charge-state $^{124}Xe^{49+,50+,51+}$ and two-charge state $^{86}Kr^{33+,34+}$ were also accelerated and delivered to the beam dump with 100% transmission

Phasing of SC cavities
Beam energy vs time



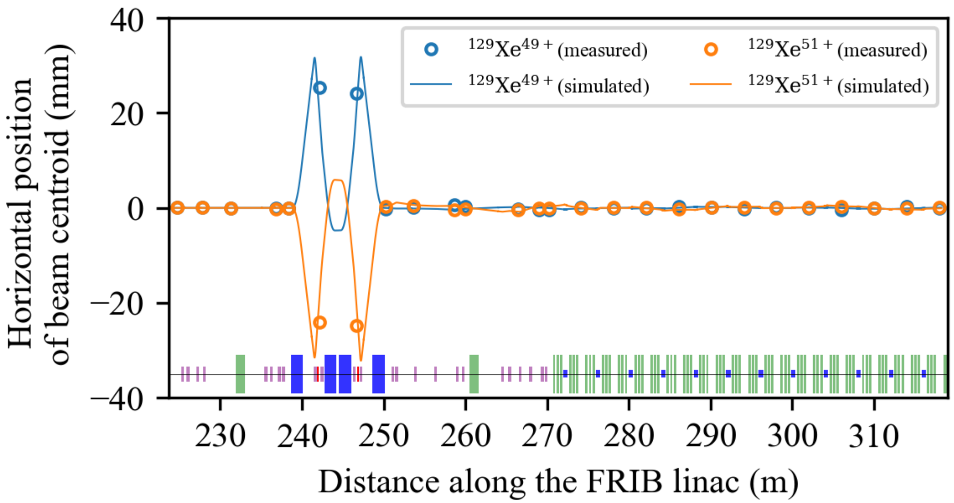
Transmission of ^{36}Ar, beam current in μA

Stripper Charge Selector

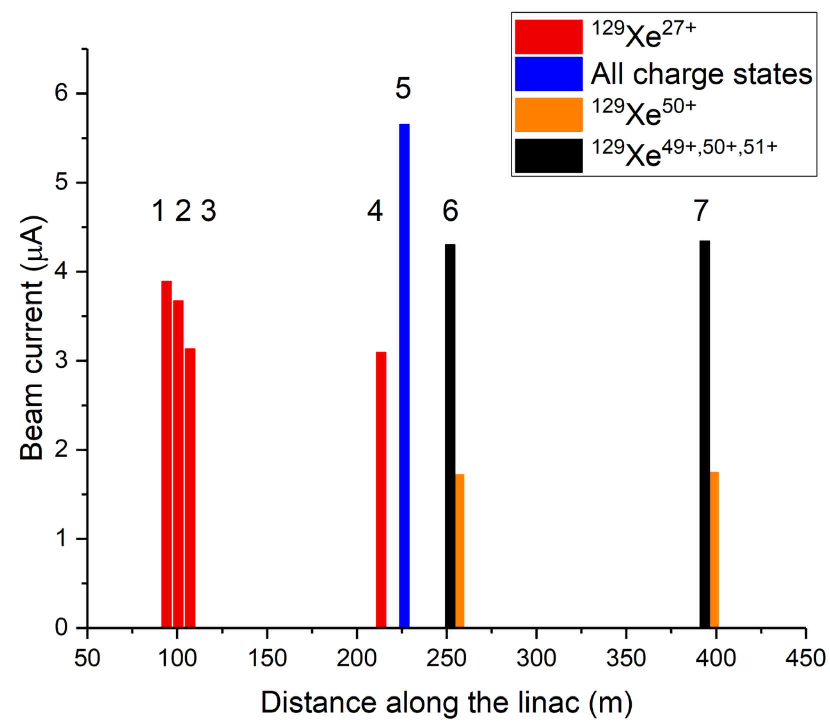


Factor of 2.5 Increase of Beam Intensity with Three Charge States Acceleration of Xe

- Simultaneous acceleration of 3 charge states of ^{129}Xe
  - Transmission is 100%
  - Stripping efficiency into 50+ = 30.5%
  - Stripping efficiency into 49+,50+, 51+=76.5%
- Multi-charge beam phase space was recombined after the dispersive magnetic system

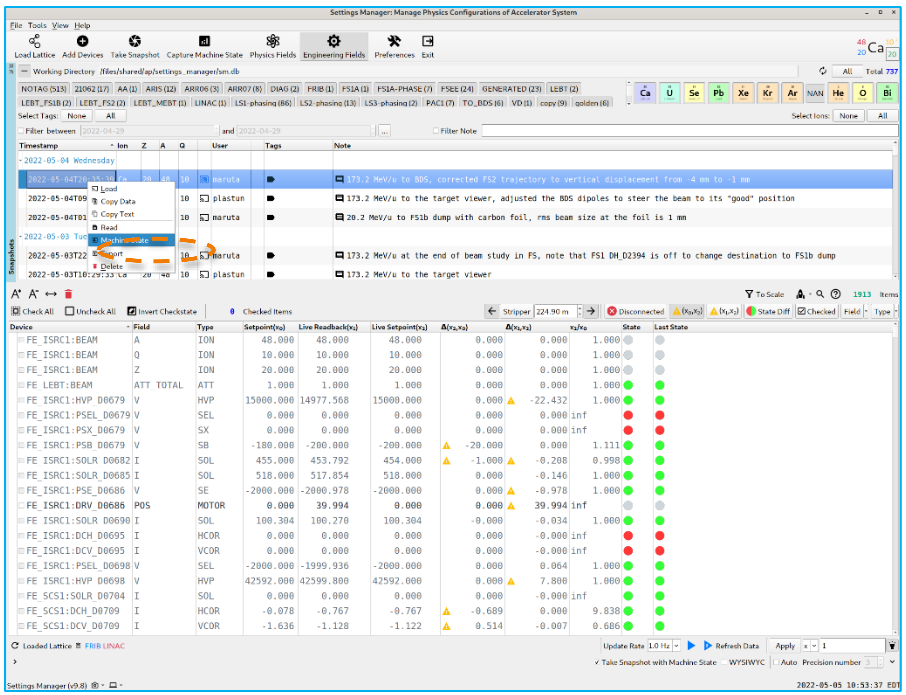


Beam current along the linac

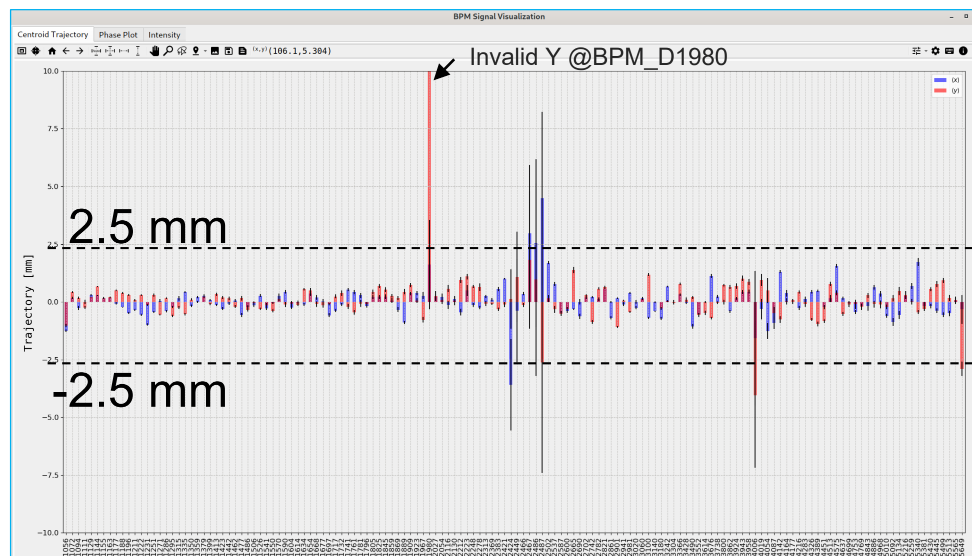


Development of HLAs to Save/Restore Both Machine and Beam Status

- Updated the Settings Manager (Management application of device settings) to save diagnostics (BPMs, BCMs and BLMs)
  - Reference values of automated tuning for the operation with the restored device setting
  - New window is developed to check saved BPM signals

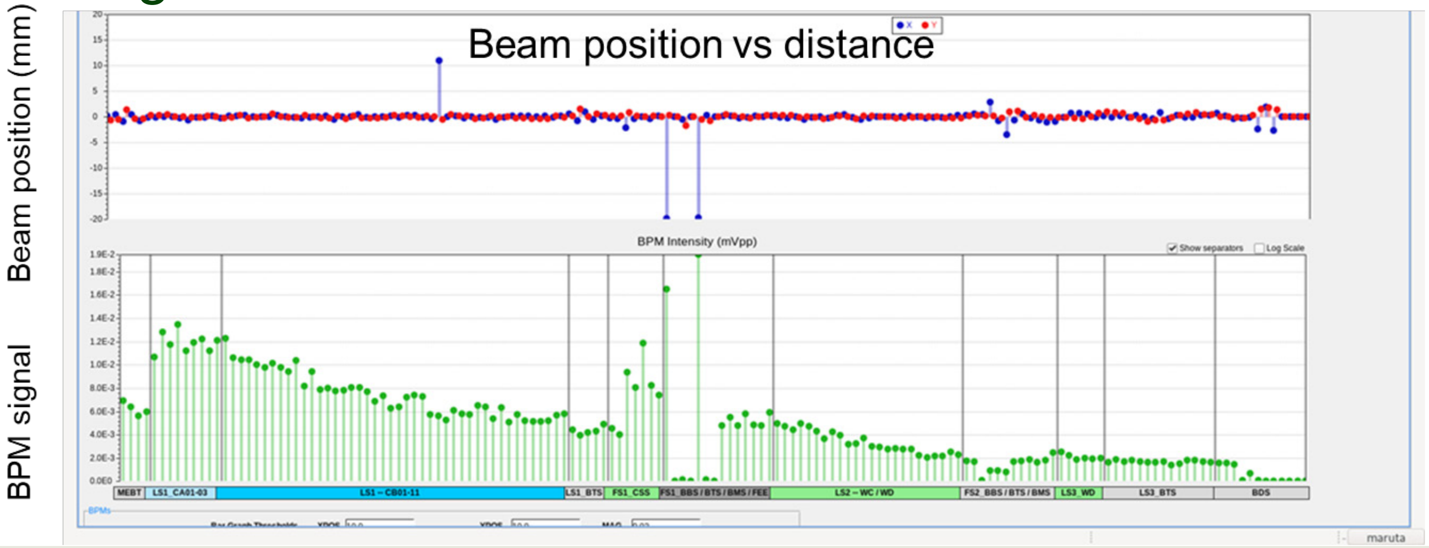


BPM readings along the linac



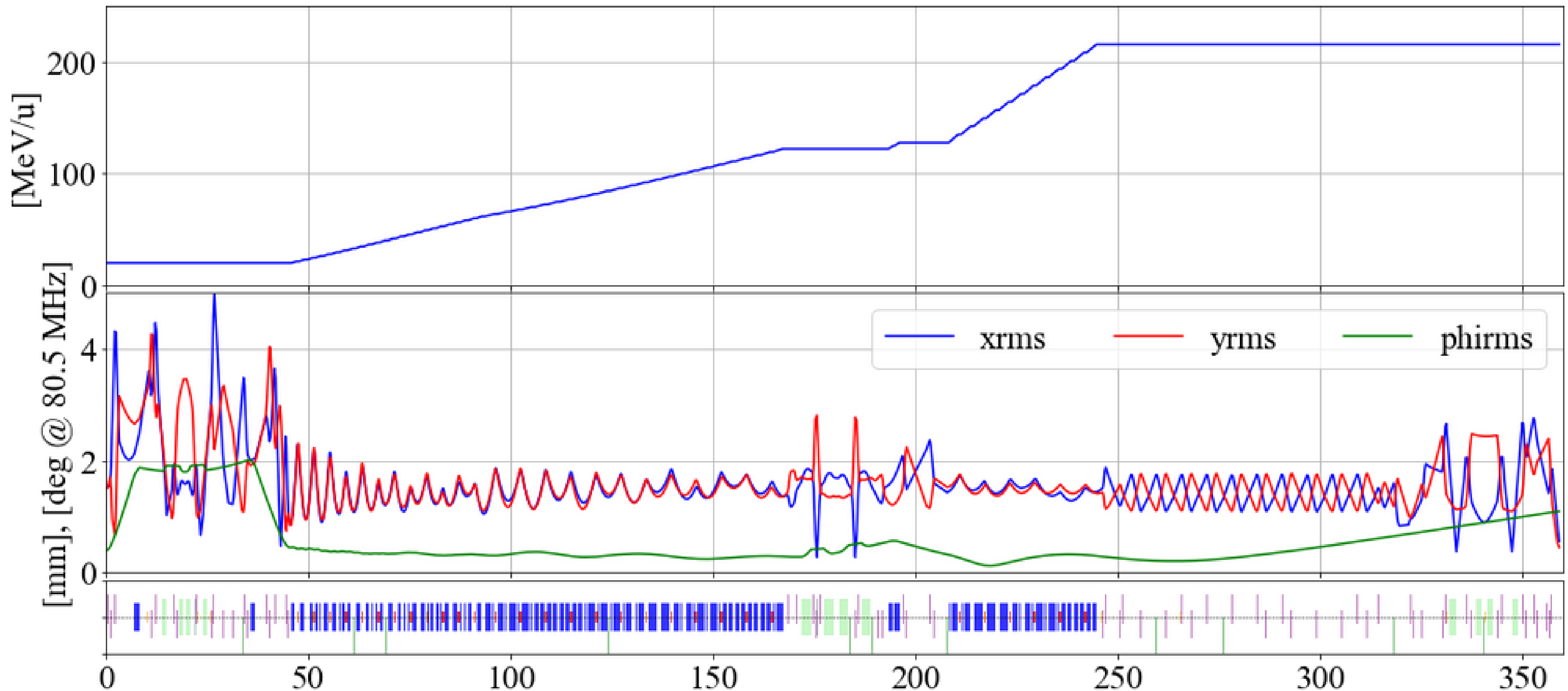
Model-Based Beam Central Trajectory Correction

- 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
- In combination with model-based phase setting reduces machine tuning/setting time to 3-4 hours



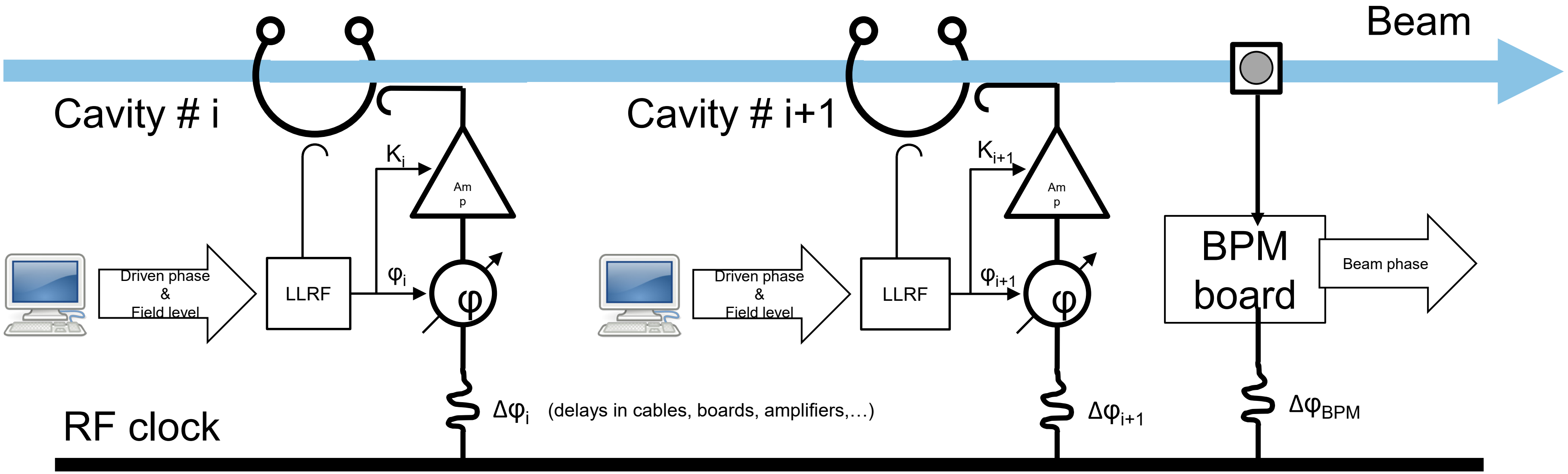
3D Computer Model Setting is Applied for Entire Linac

- 210 MeV/u ^{36}Ar tune for the commissioning of Fragment Separator
- Measured beam parameters are consistent with the simulations



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



- Model

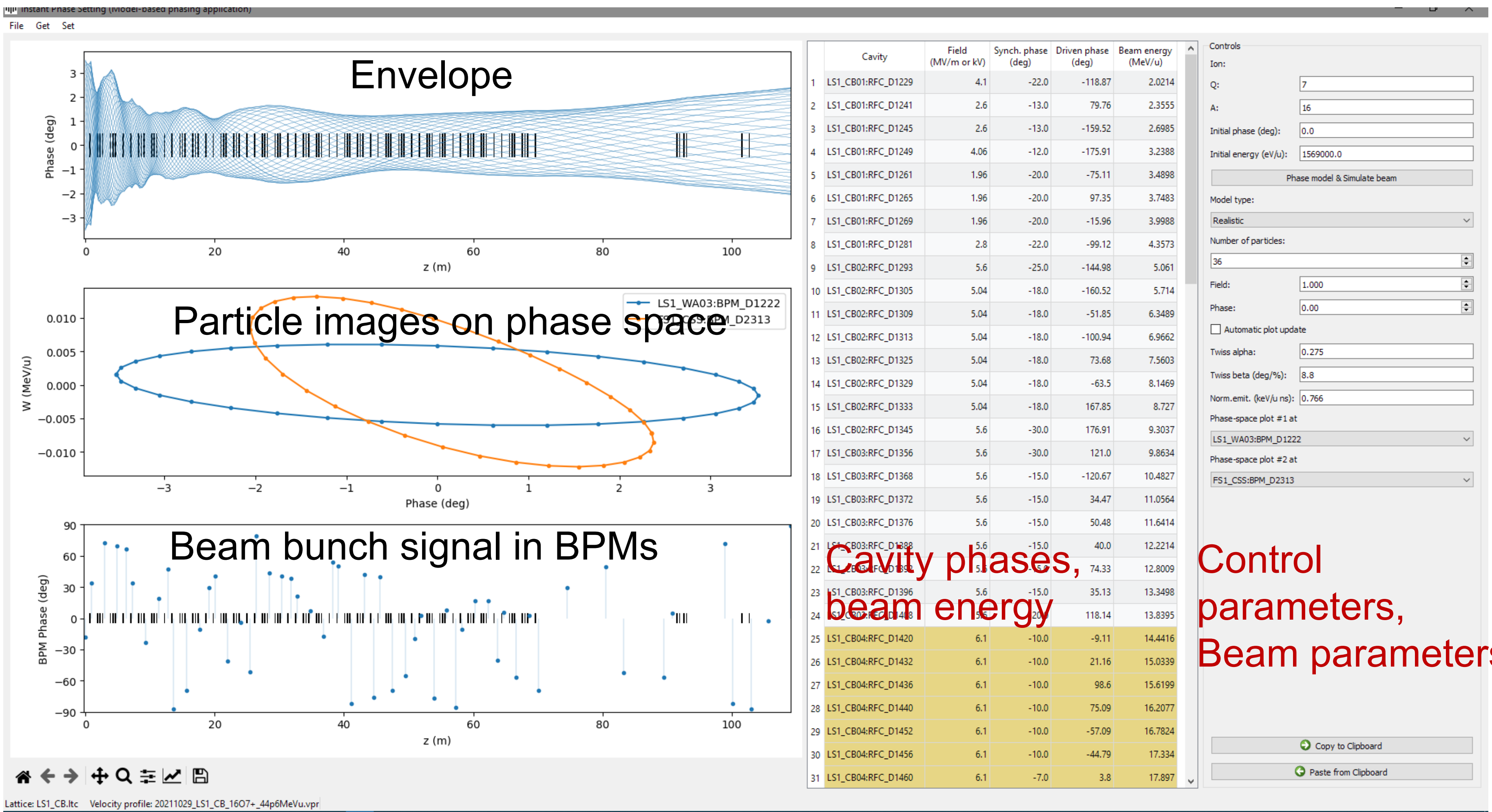
Cavity field: $E_i = K_i E_0 \cos(2\pi f t + \Delta\varphi_i + \varphi_i)$

$$\begin{cases} \dfrac{dW}{dz} = qE_z(z) \\ \dfrac{dt}{dz} = \dfrac{1}{v_z} \end{cases}$$

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

Screenshot of Instant Phase Setting (IPS) Application

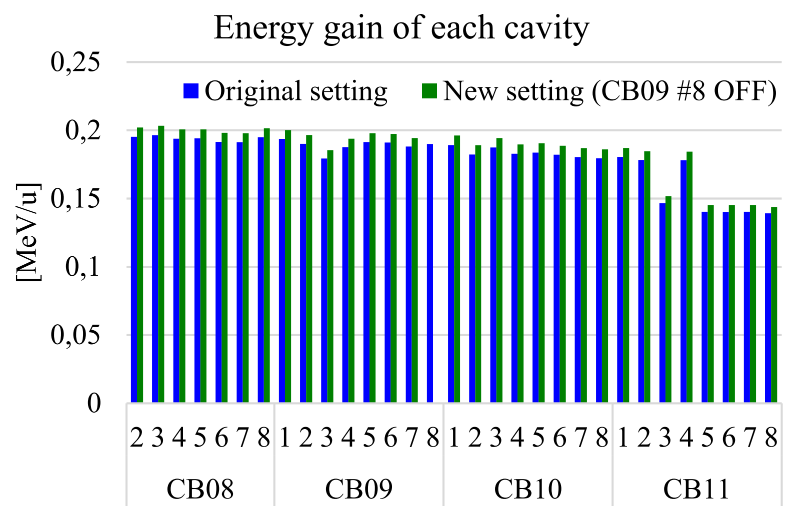
- The phasing of the cavity is based on calibration data and accelerator model, LS1-104 cavities, LS2 – 168, LS3 - 52



	Cavity	Field (MV/m or kV)	Synch. phase (deg)	Driven phase (deg)	Beam energy (MeV/u)
1	LS1_CB01:RFC_D1229	4.1	-22.0	-118.87	2.0214
2	LS1_CB01:RFC_D1241	2.6	-13.0	79.76	2.3555
3	LS1_CB01:RFC_D1245	2.6	-13.0	-159.52	2.6985
4	LS1_CB01:RFC_D1249	4.06	-12.0	-175.91	3.2388
5	LS1_CB01:RFC_D1261	1.96	-20.0	-75.11	3.4898
6	LS1_CB01:RFC_D1265	1.96	-20.0	97.35	3.7483
7	LS1_CB01:RFC_D1269	1.96	-20.0	-15.96	3.9988
8	LS1_CB01:RFC_D1281	2.8	-22.0	-99.12	4.3573
9	LS1_CB02:RFC_D1293	5.6	-25.0	-144.98	5.061
10	LS1_CB02:RFC_D1305	5.04	-18.0	-160.52	5.714
11	LS1_CB02:RFC_D1309	5.04	-18.0	-51.85	6.3489
12	LS1_CB02:RFC_D1313	5.04	-18.0	-100.94	6.9662
13	LS1_CB02:RFC_D1325	5.04	-18.0	73.68	7.5603
14	LS1_CB02:RFC_D1329	5.04	-18.0	-63.5	8.1469
15	LS1_CB02:RFC_D1333	5.04	-18.0	167.85	8.727
16	LS1_CB02:RFC_D1345	5.6	-30.0	176.91	9.3037
17	LS1_CB03:RFC_D1356	5.6	-30.0	121.0	9.8634
18	LS1_CB03:RFC_D1368	5.6	-15.0	-120.67	10.4827
19	LS1_CB03:RFC_D1372	5.6	-15.0	34.47	11.0564
20	LS1_CB03:RFC_D1376	5.6	-15.0	50.48	11.6414
21	LS1_CB03:RFC_D1388	5.6	-15.0	40.0	12.2214
22	[illegible]	[illegible]	[illegible]	74.33	12.8009
23	LS1_CB03:RFC_D1396	5.6	-15.0	35.13	13.3498
24	[illegible]	[illegible]	[illegible]	118.14	13.8395
25	LS1_CB04:RFC_D1420	6.1	-10.0	-9.11	14.4416
26	LS1_CB04:RFC_D1432	6.1	-10.0	21.16	15.0339
27	LS1_CB04:RFC_D1436	6.1	-10.0	98.6	15.6199
28	LS1_CB04:RFC_D1440	6.1	-10.0	75.09	16.2077
29	LS1_CB04:RFC_D1452	6.1	-10.0	-57.09	16.7824
30	LS1_CB04:RFC_D1456	6.1	-10.0	-44.79	17.334
31	LS1_CB04:RFC_D1460	6.1	-7.0	3.8	17.897

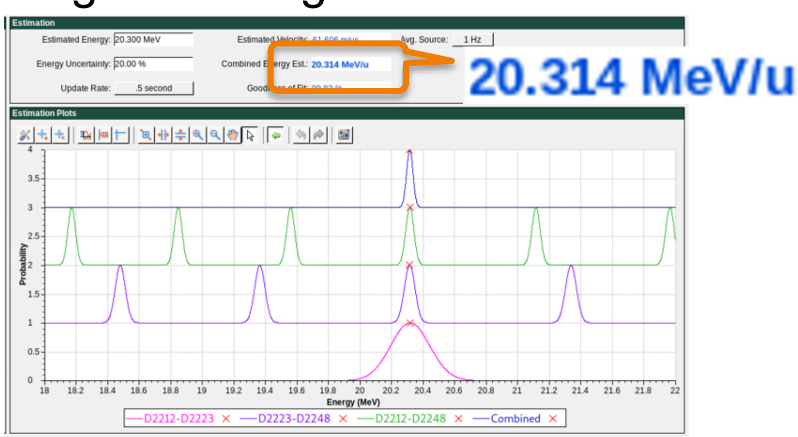
IPS Was Applied to Tune around Cavity Failure

- Example: CB09 #8 cavity was tripped and hard to restart
- Alternative cavity setting was developed by IPS so that beam energy is recovered to 20.3 MeV/u without the faulted cavity
  - Set smaller synchronous phase angle in CB08 cavities
  - Re-setting took 10 min but can be significantly reduced in future, less than 1 min
- The energy difference is only 7 keV/u



Beam energies after LS1

Original setting

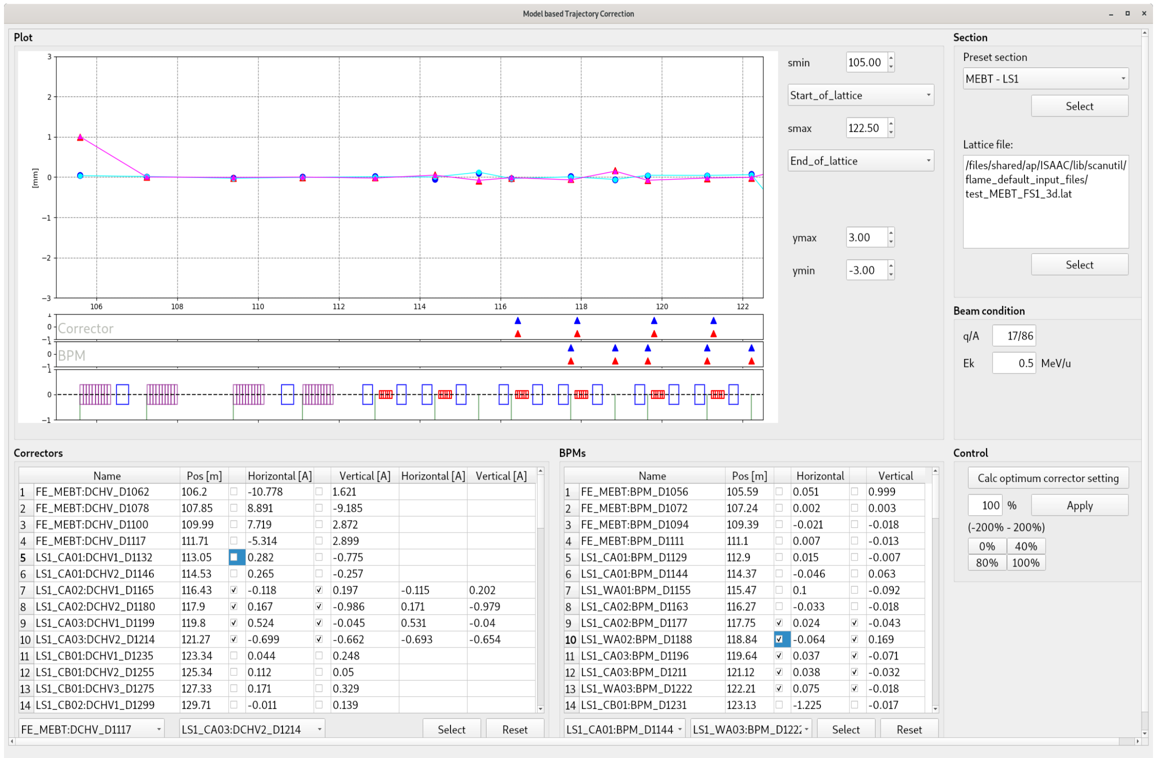


New setting

Trajectory Correction

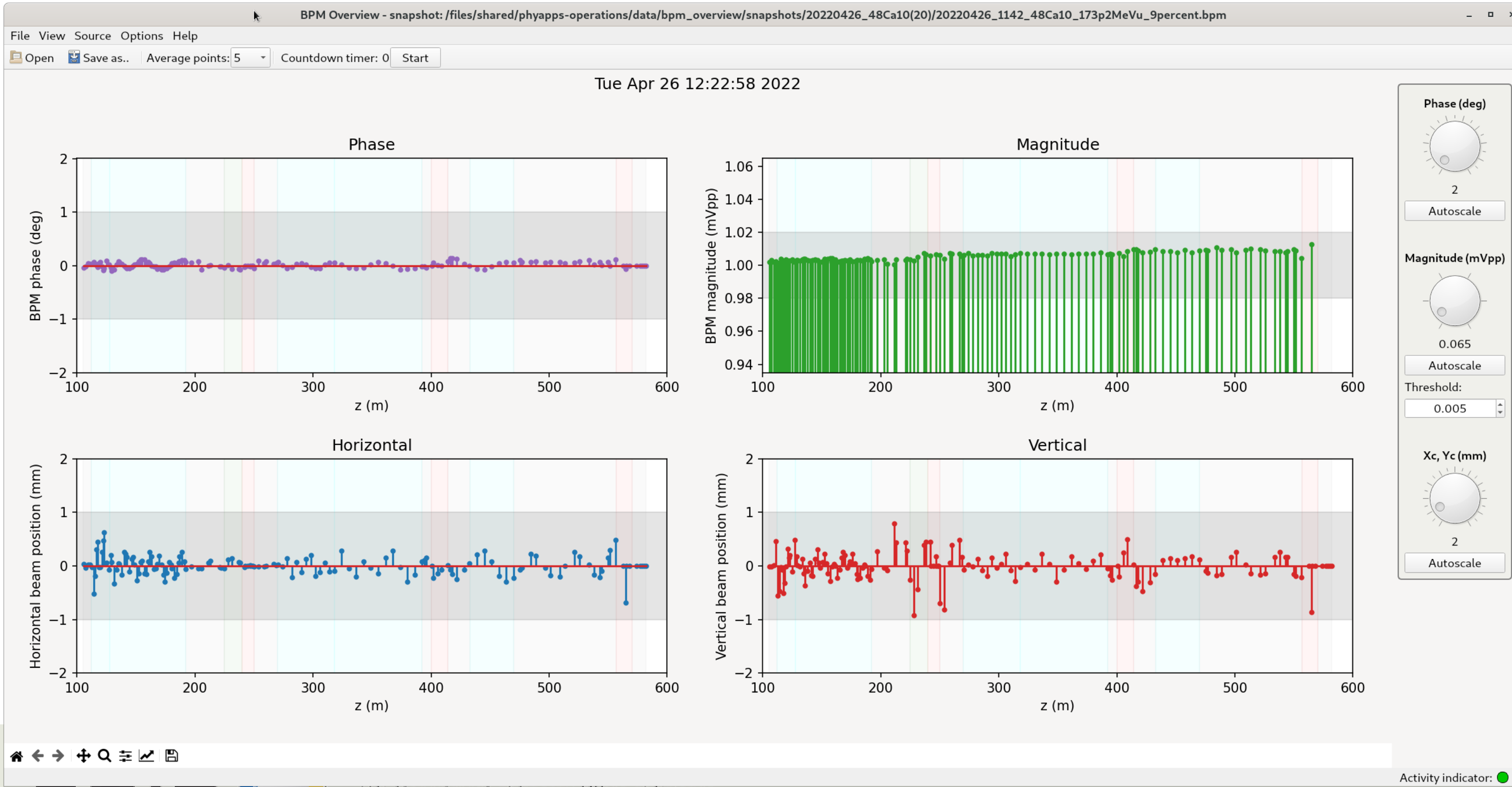
Extending to Tune the Entire Segment by One Knob

- Trajectory Correction application has been in use since 2019
  - ORM method with measurement-based beam response
  - LS1 CB05 to 06 were tuned in about 30 minutes in September 2019
    - » Spent most of time to measure BPM response to upstream corrector change
- Implemented model-based trajectory correction application in 2021
  - Calculate response matrix by envelope code FLAME
  - Applied to tune several cryomodules in a few minutes
- This application will be upgraded to series of tuning for the entire LS by one knob



Beam Status in the Linac for Operators

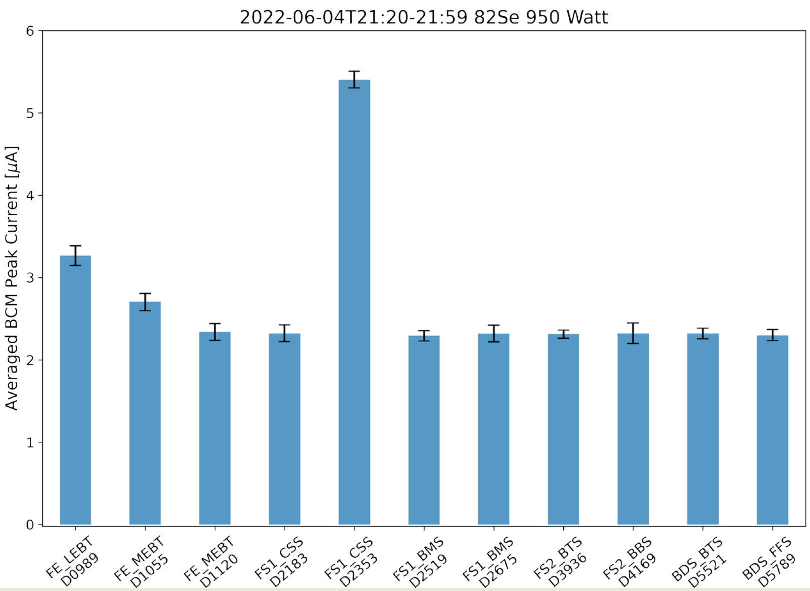
- After the completion of the reference tune, the operators can observe beam status in the linac using the signals from 144 BPMs



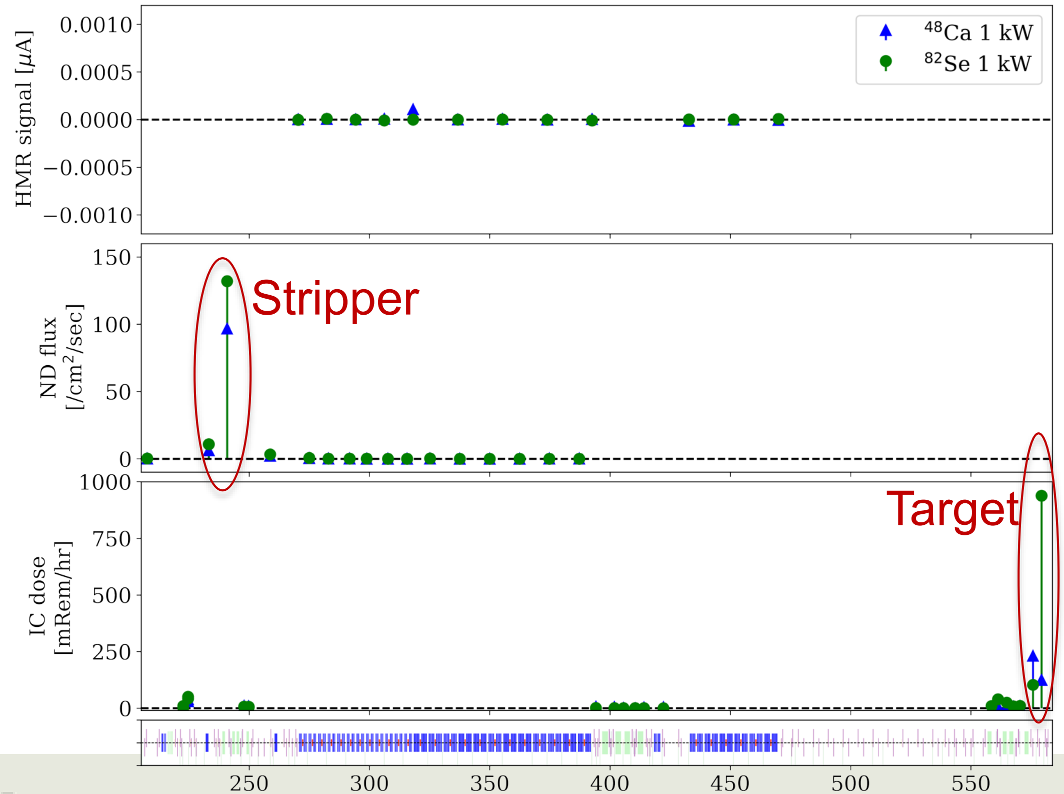
One Kilowatt Primary Beams

- 1-kW ^{48}Ca and ^{82}Se were provided for user experiments in May-June
- No uncontrolled beam losses in the linac

Beam current along the linac



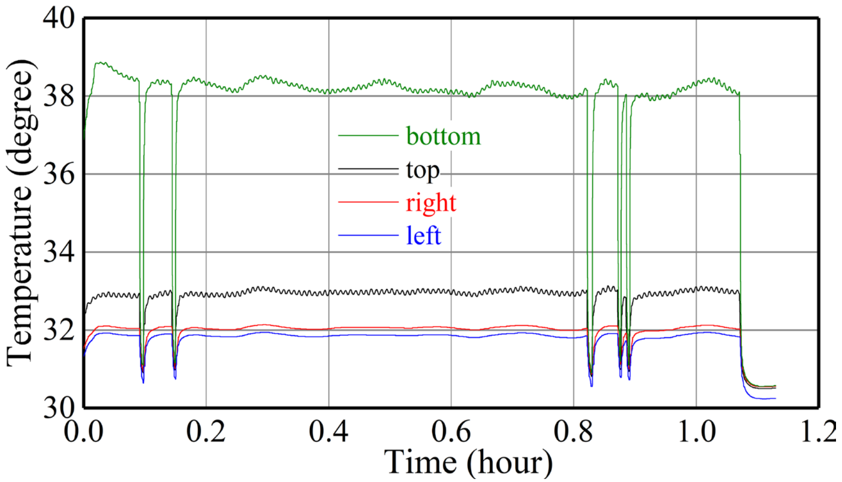
Beam losses measured by Halo Monitor Rings, Neutron Detectors and Ionization Chambers



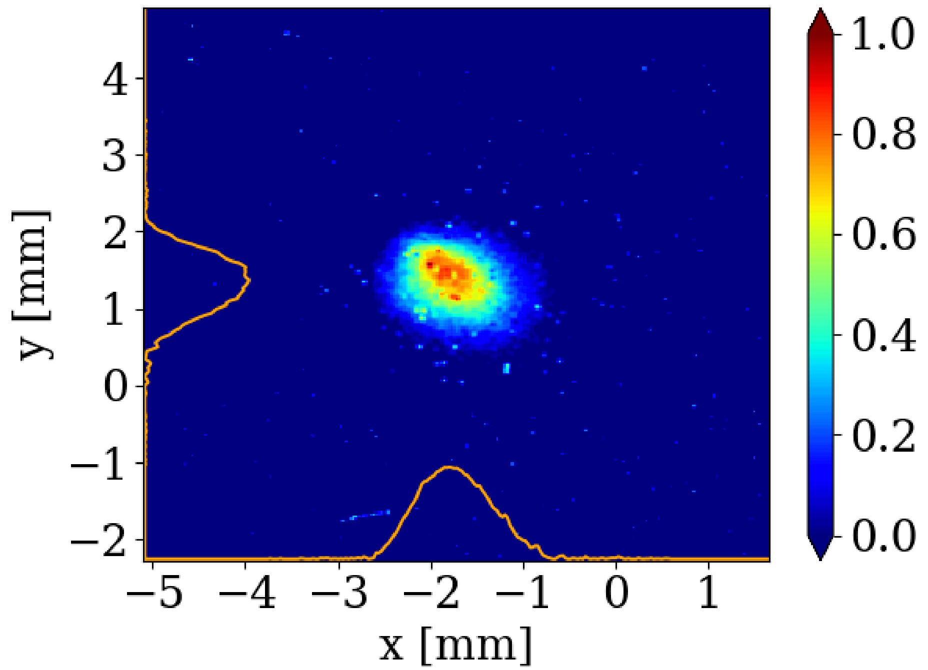
One Kilowatt Beam on Target

- The primary beam is tuned on target with 0.3 mm rms radius
- There is 4-segment collimator upstream of the target
  - The temperature sensors show the heating of the collimator due to beam halo

Temperature readings from each collimator segment



^{82}Se beam image on beryllium target



Summary

- Beam commissioning of the FRIB is complete
  - The facility is in operation since April 2022
- Our experience shows that the linac model (online and offline) predicts the beam dynamics very well except for transverse beam steering due to misalignments
- Automation of Linac is essential to increase beamtime for science
  - Many HLAs have been developed for efficient beam tuning
  - There is significant potential to improve the machine performance and reduce setting for each experiment
  - Machine Learning studies and application started in the Front End and will be extended to downstream sections
- The first 2 User experiments were conducted in May-June 2022
  - PAC1 approved 34 experiments
- The power ramp-up is being implemented in phases