FRIB accelerator science and technology challenges

Peter Ostroumov

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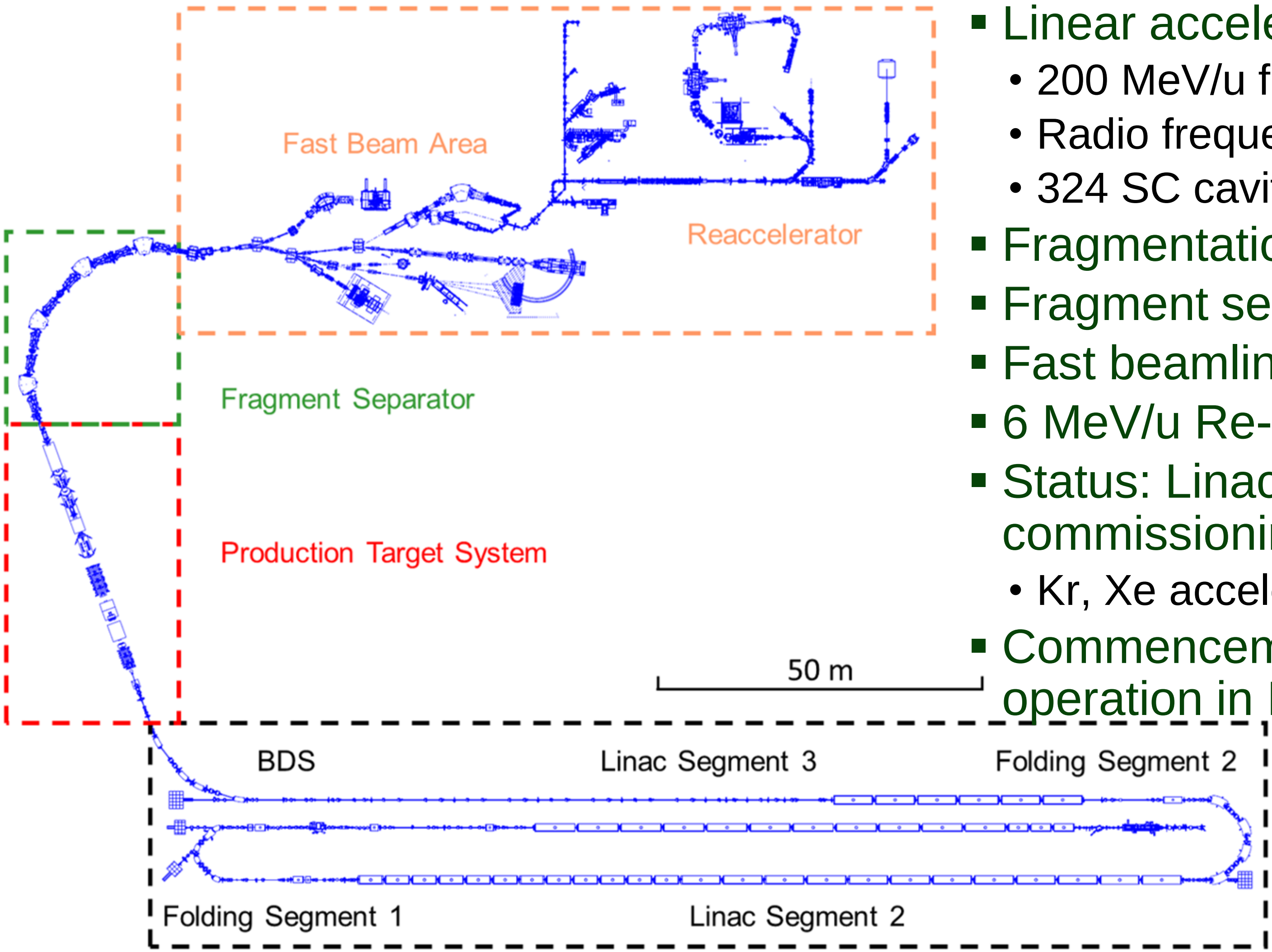
Content

- Facility layout
- FRIB accelerator science and technology challenges and status
- Discussion of state-of-the-art accelerator systems
- Liquid lithium stripper
- Multiple charge state acceleration
- Results of beam commissioning of entire linac
- Toward the final milestones of the project
  - Demonstration of Se-84
  - Delivery of the beam to the S800 spectrometer
- Summary

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 Accelerator Science and Technology Challenges and Status (1)

	Technology Challenges	Status
✓	80.5 MHz CW RFQ for lowest q/A=1/7	Conditioned for uranium. Auto-start after occasional sparks within ~30 sec
✓	SRF: mass production of cavities and cryomodules	324 SC cavities of 4 types in 46 cryomodules operate at the design level of gradients +10% margin
✓	Large cryogenic facility	Operational with 100% availability
✓	Large SC dipoles, multipole magnets	Four 6 T·m dipoles operational in linac. Two 140 ton (cold) and two 110 ton magnets, 8 T·m , installed. 30-cm aperture triplets installed and several of them are cold.
✓	Liquid lithium stripper	Successfully tested with Ar, Xe and U beams
✓	Digital LLRF for multiple frequencies and multiple tuner types	Operational. Accuracy of field amplitude is ±0.1% and phase ±0.2°
✓	Targetry: beam target, beam dump, wedges for high power ion beams	Phased approach. We start with 10 kW for PAC1 period.

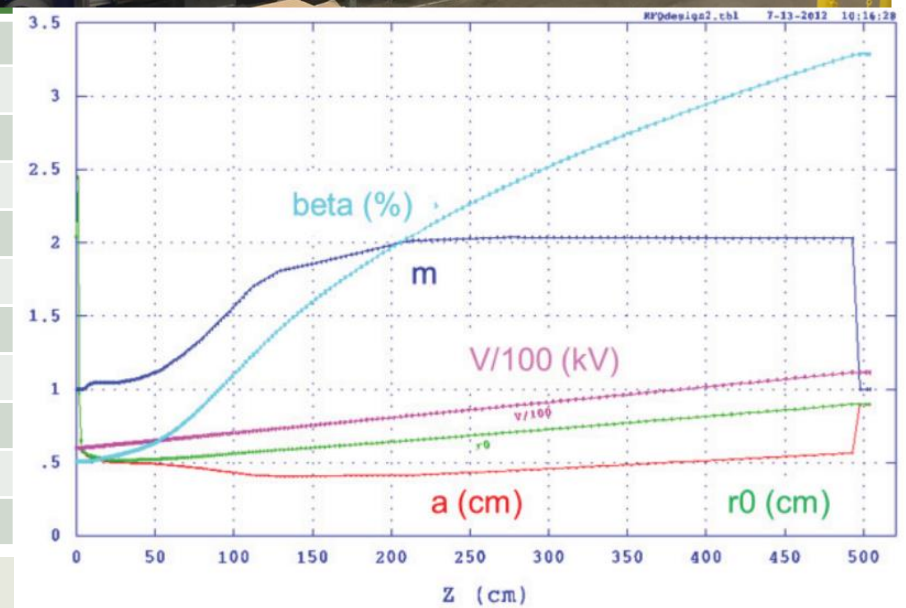
FRIB Accelerator Science and Technology Challenges and Status (2)

	Technology and AP Challenges	Status
✓	Machine Protection System	Operational in the linac. Beam can be stopped at LEBT within 35 μs
✓	Isotope detectors: fast timing, in-flight PID	We start with NSCL detectors. Advanced detectors are under development.
✓	Multiple charge state acceleration	Successfully demonstrated
✓	High Level Applications	Many HLAs in use. New developments including ML to minimized time for machine setting
✓	Beam losses below 10^{-4}	Demonstrated for 17.5 pμA argon beam in pulsed mode, 200 kW equivalent
✓	Operational challenge: high availability	Multi-prong approach: failure analysis of all devices; spares; preventive maintenance; HLAs for quick setting
✓	Future expansion of the facility	There is a space in the tunnel for 400 MeV/u upgrade. A space is available for additional fragmentation or ISOL target.

Radio Frequency Quadrupole

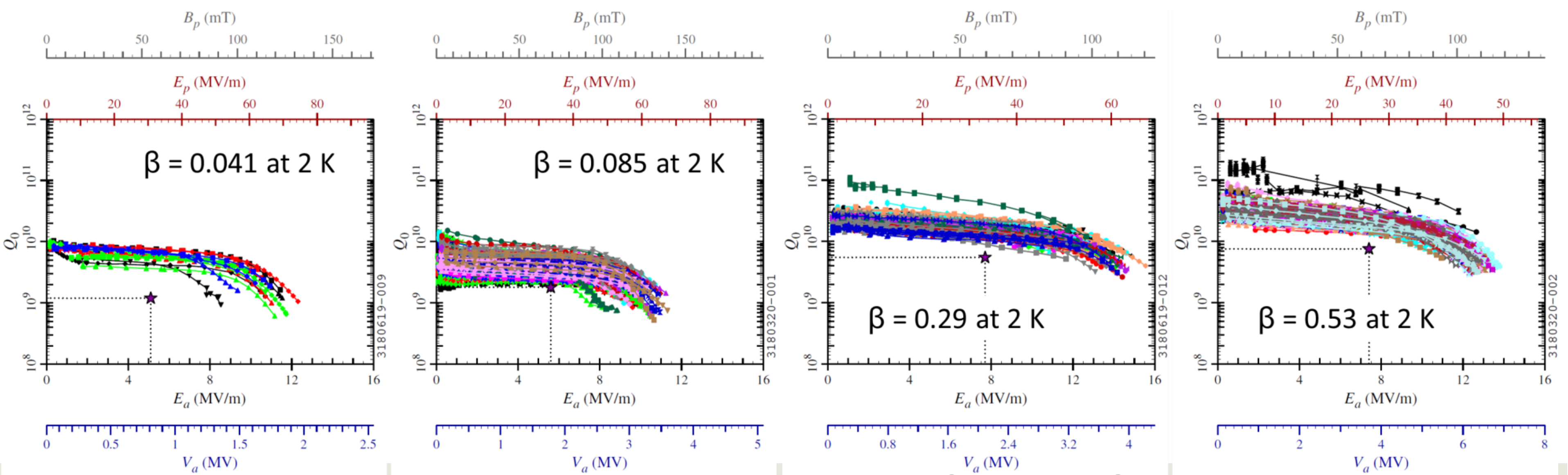
- Unique parameters:
  - CW
  - Voltage is high, 112 kV
  - Variable R_0 and voltage
  - q/A=1/7
- Conditioned at the design voltage
  - Tested with uranium beam

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



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 accomplisheds
- 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



Courtesy SRF Department

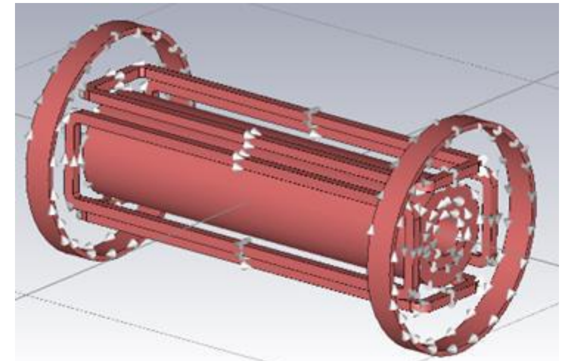
SRF Cryomodules

Example of cryomodules' cold mass

β = 0.53

β = 0.085

Cryomodules include SC magnet assembly of solenoid and dipole coils

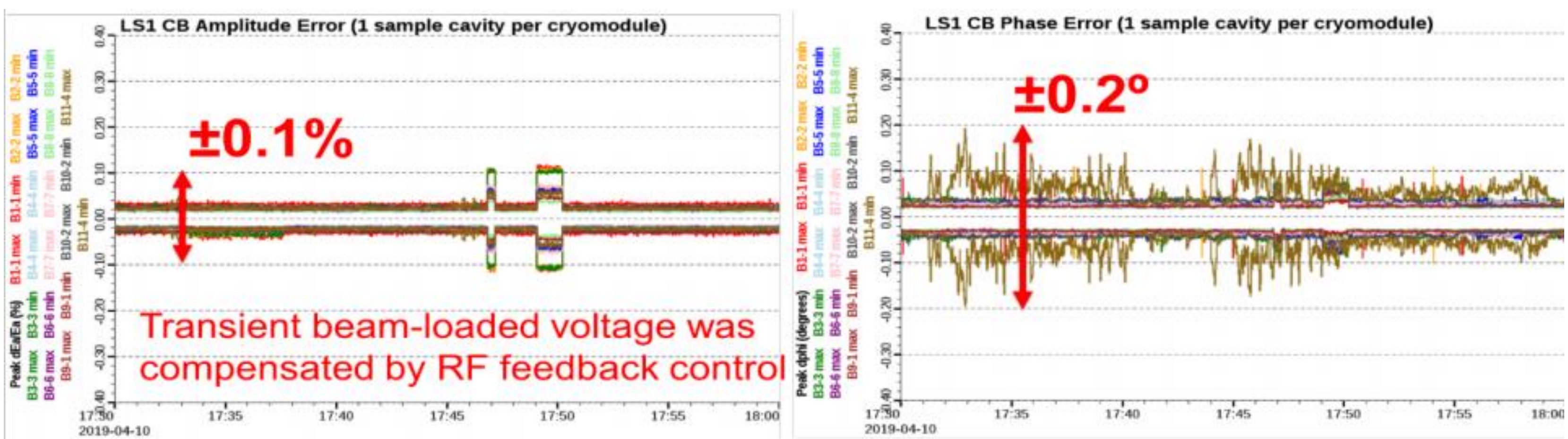


All 46 cryomdules installed in the tunnel

FRIB LLRF Challenges

- Digital LLRF to support multiple frequencies
  - RF inputs, same circuit for all frequencies from 40.25 MHz to 322 MHz
    - » Direct sampling; No mixer, no local oscillator, digital mixing to eliminate thermal effects
  - RF output, three variants each supports two frequencies
    - » Direct synthesis; Use band-pass filters to pickup fundamental or higher harmonics. No mixer, no local oscillator
- Supports all tuners: water flow, 2 or 5 phase stepper, pneumatic, external servo, error posting (RFQ)

LLRF was tested with pulsed beam loading

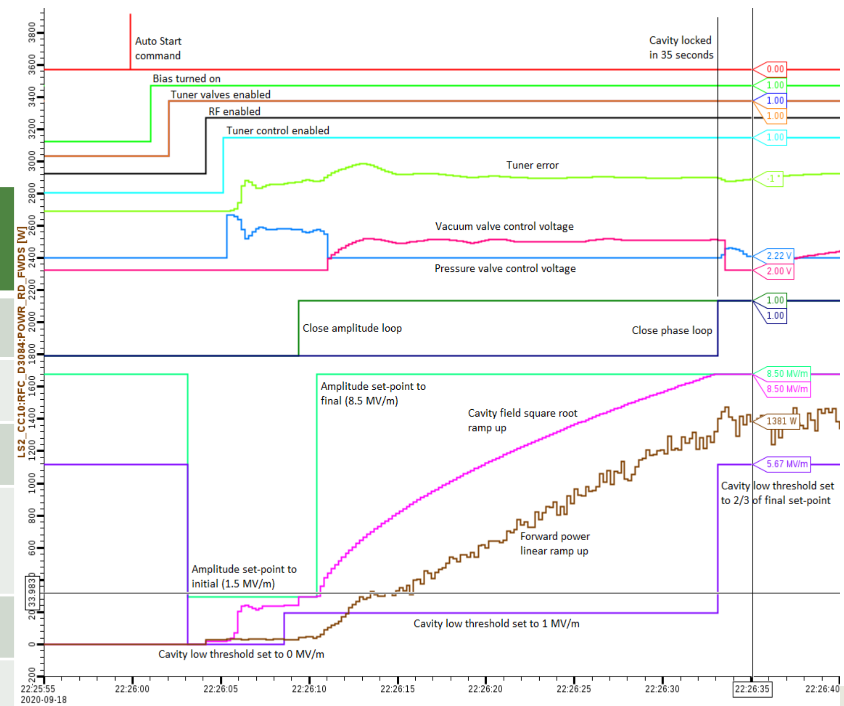


Auto-Start of Resonators

- 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 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



Facility for Rare Isotope Beams
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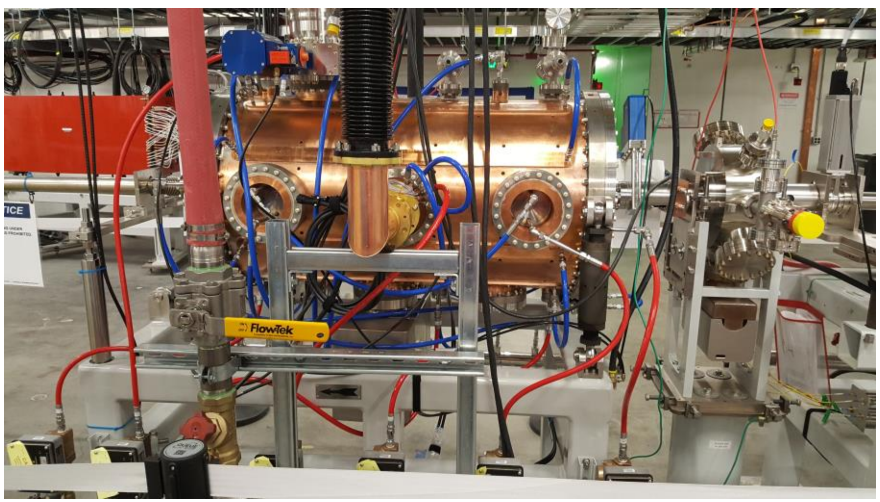
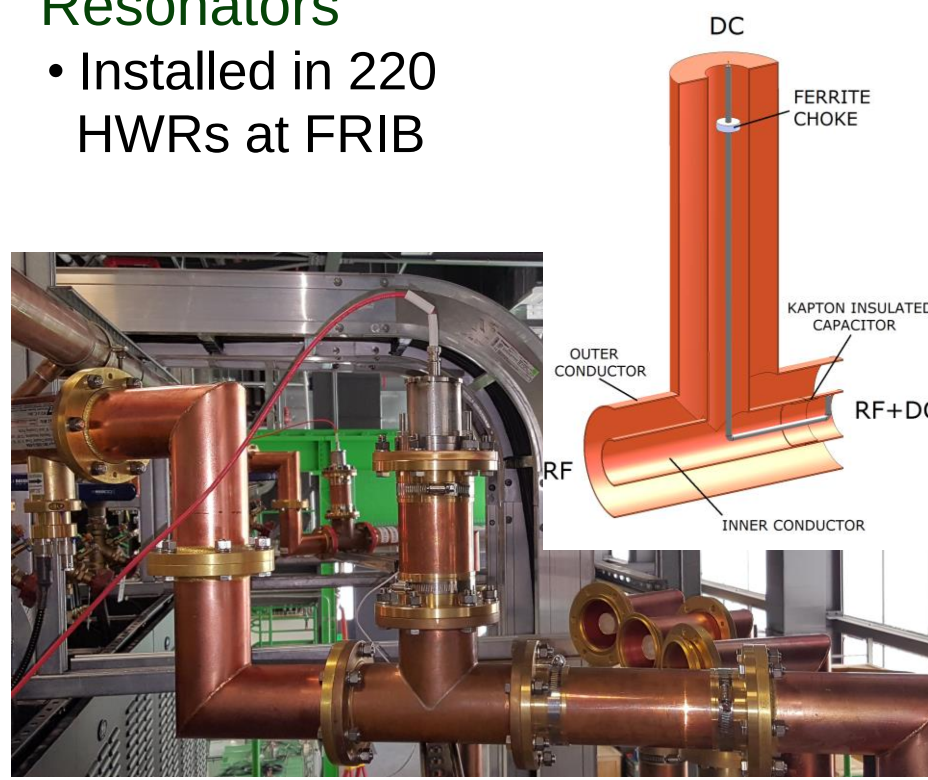
Selected Innovations

- Two 161 MHz RF bunchers were developed and built to replace two cryomodules at 20 MeV/u
- CW operation

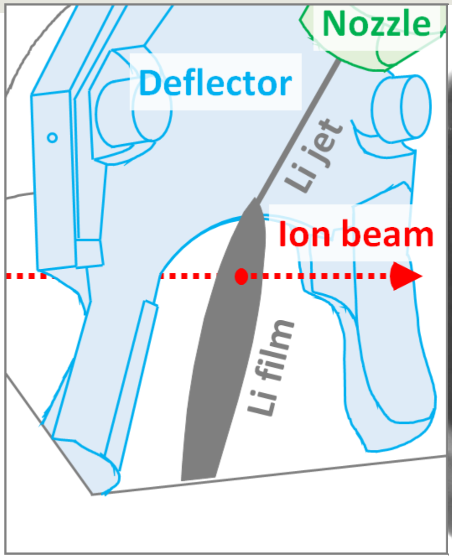


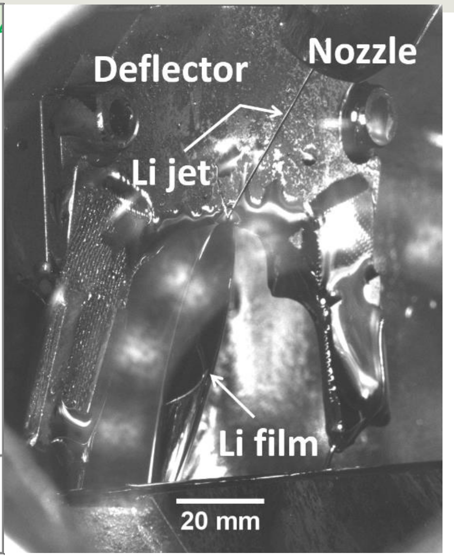
- DC bias-T for coaxial transmission lines to prevent multipacting in a coupling antenna in 322 MHz Half Wave Resonators
  - Installed in 220 HWRs at FRIB



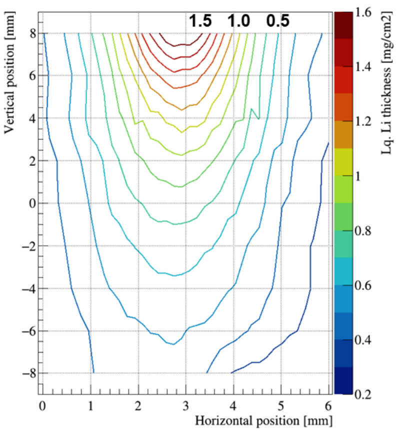
Liquid Lithium Stripper

- 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 LS1
- 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

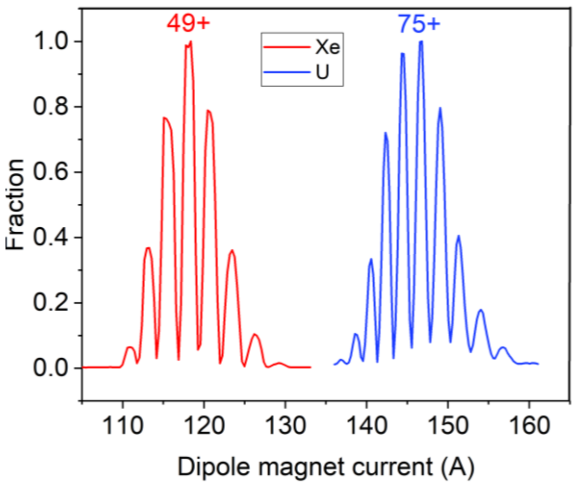




Li film thickness



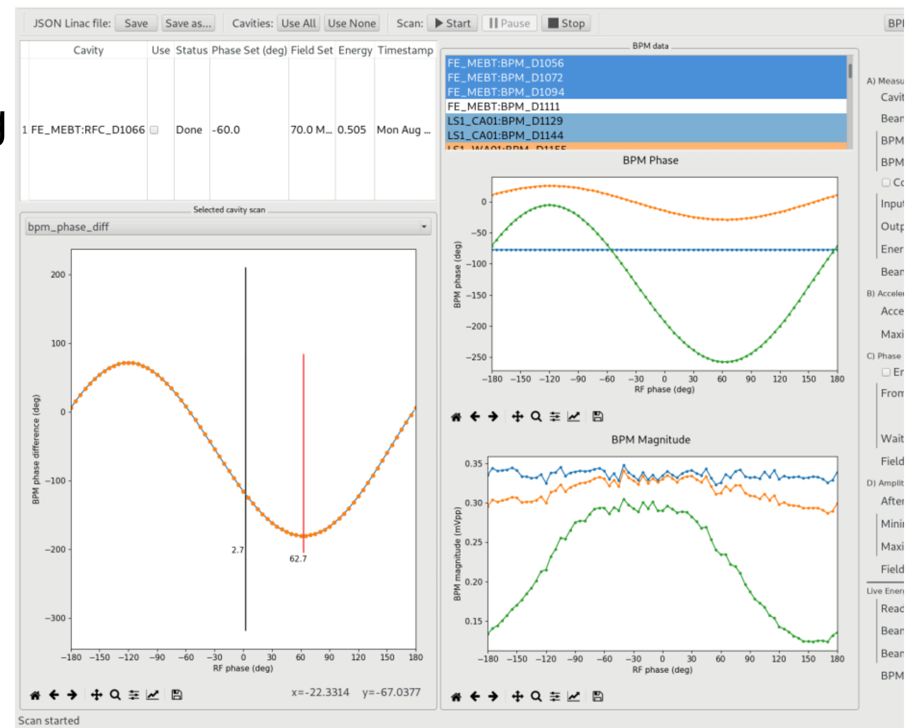
Charge distribution



Overview of the High-level Physics Controls

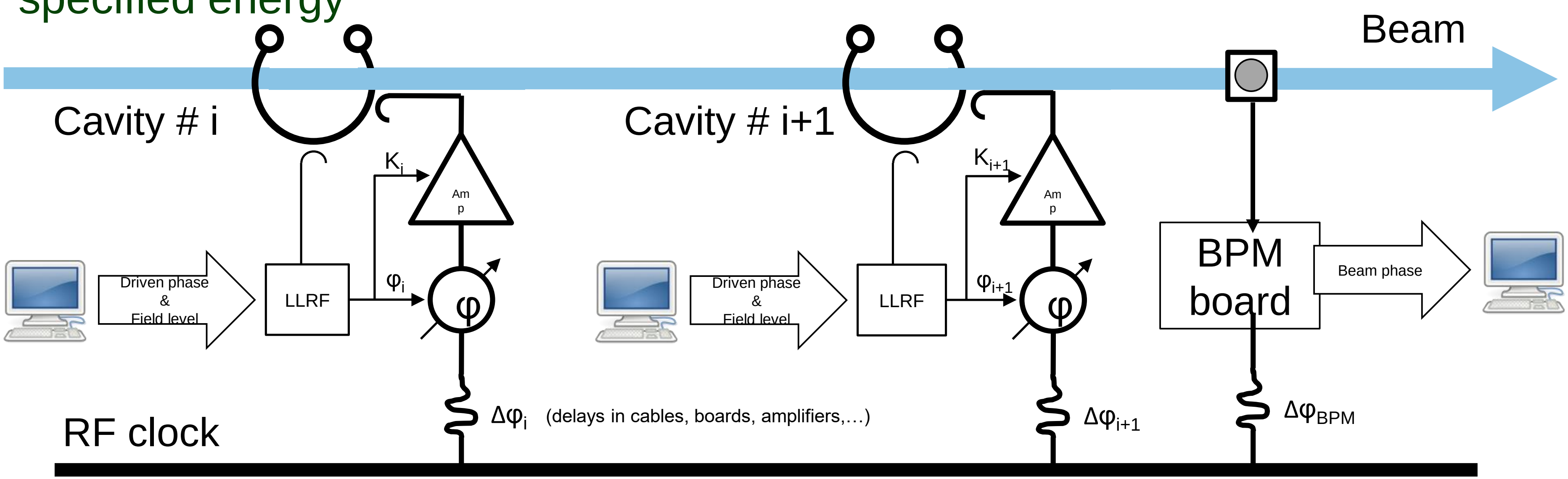
- Currently there are 20 HLAs for Linac tuning and operations support
  - Several more applications are being prepared for the setting/tuning of Advanced Rare Isotope Separator (ARIS)
- Most frequently used applications are:
  - Setting Manager
  - ALPHA: Automatic phase scan
  - BETA: Model-based optical element tuning
  - Correlation visualizer
- ALPHA : developed for an automated phasing of FRIB SC cavities and other resonators by means of time-of-flight (TOF) measurements
  - Usually about 40 cavities can be tuned sequentially without human interference
- BETA: based on on-line envelope code FLAME; quad scan for multiple profile measurements, matching of the beam centroid and Twiss parameters

ALPHA scfreen



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

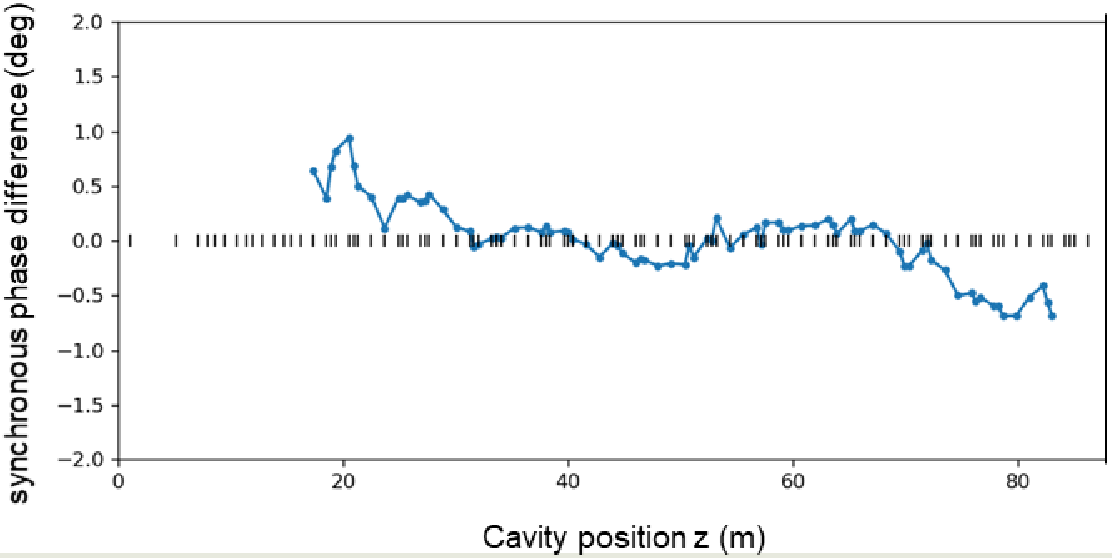
- Model

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

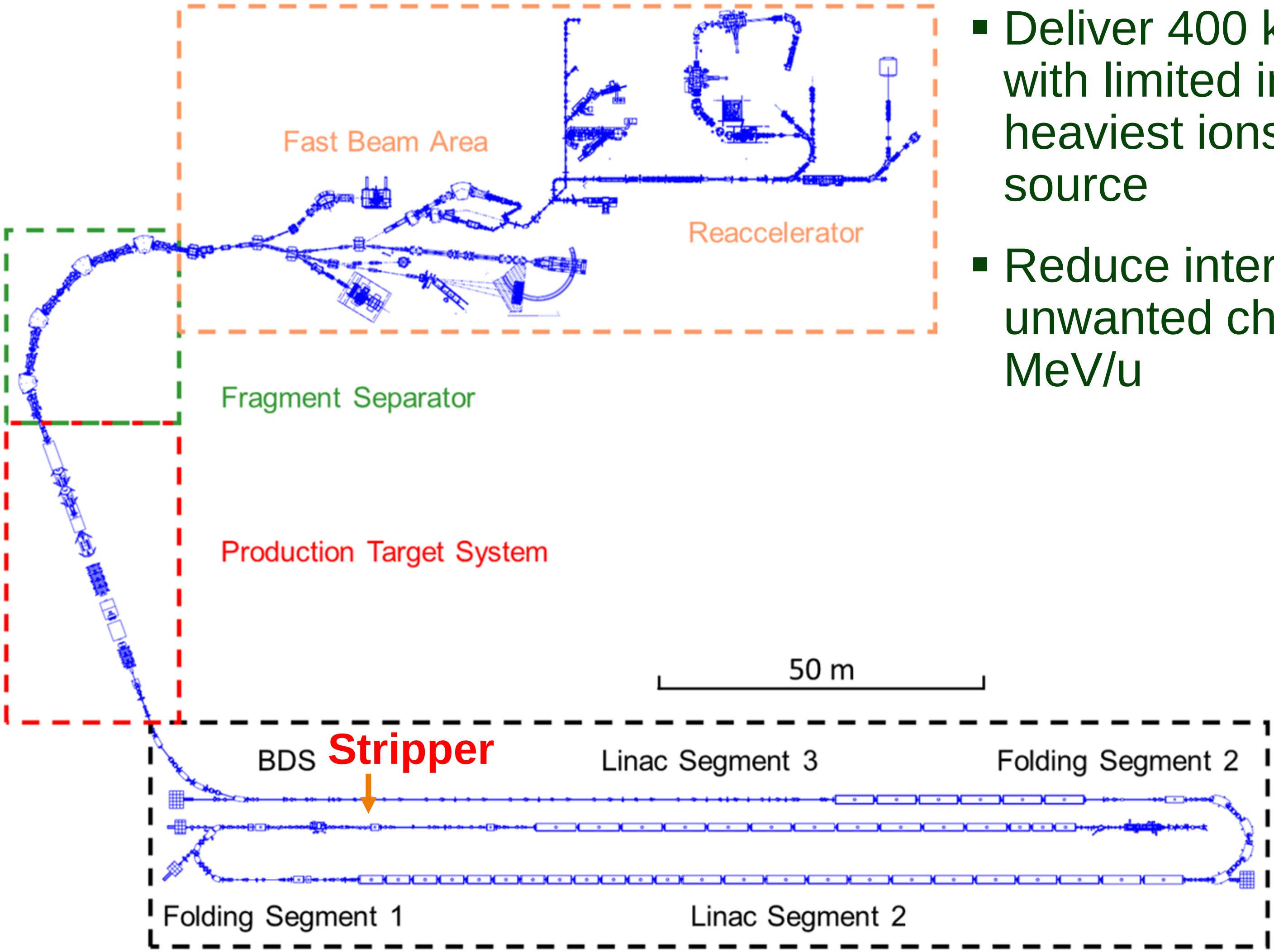
Instant Phase/Amplitude Setting in LS1

- 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 $\pm$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



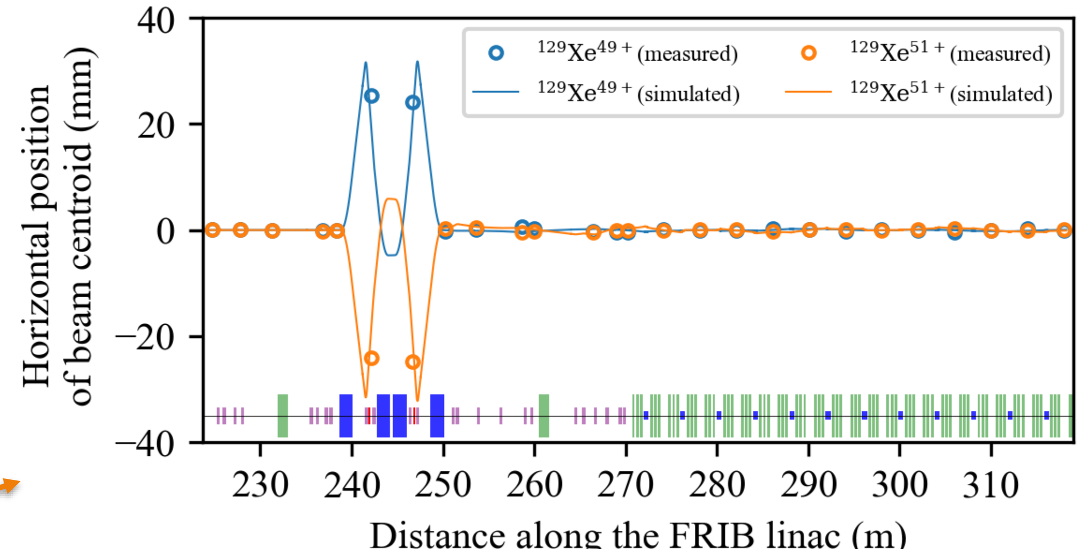
Multiple Charge State Acceleration

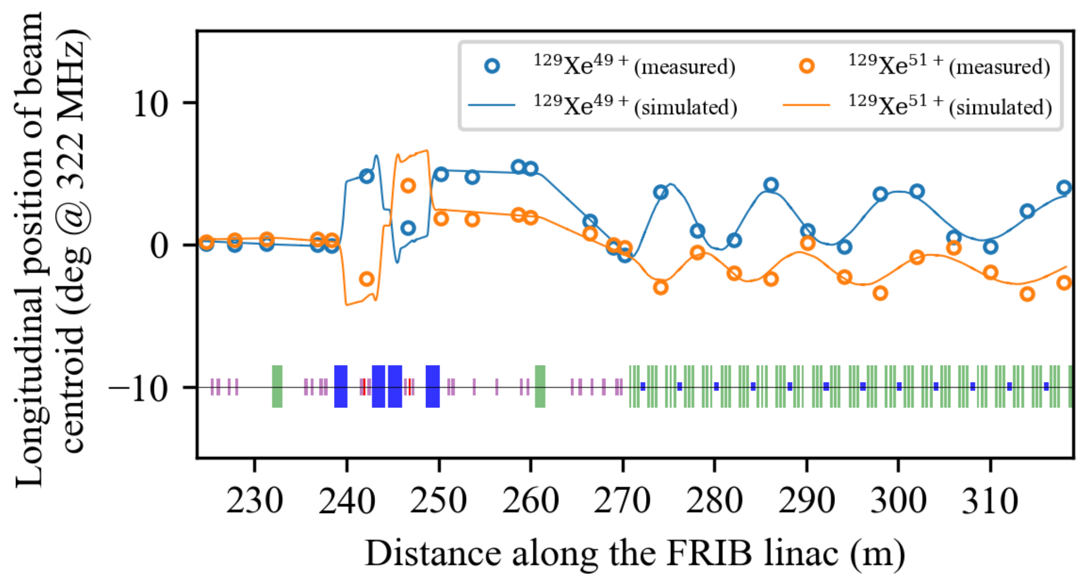


- Deliver 400 kW beam power with limited intensity of heaviest ions form the ion source
- Reduce intercepted power of unwanted charge states at 17 MeV/u

Three Charge States of Xe Accelerated Simultaneously

- Three charge states of Xenon beam from stripper to the end of CC cryomodules
- 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 a 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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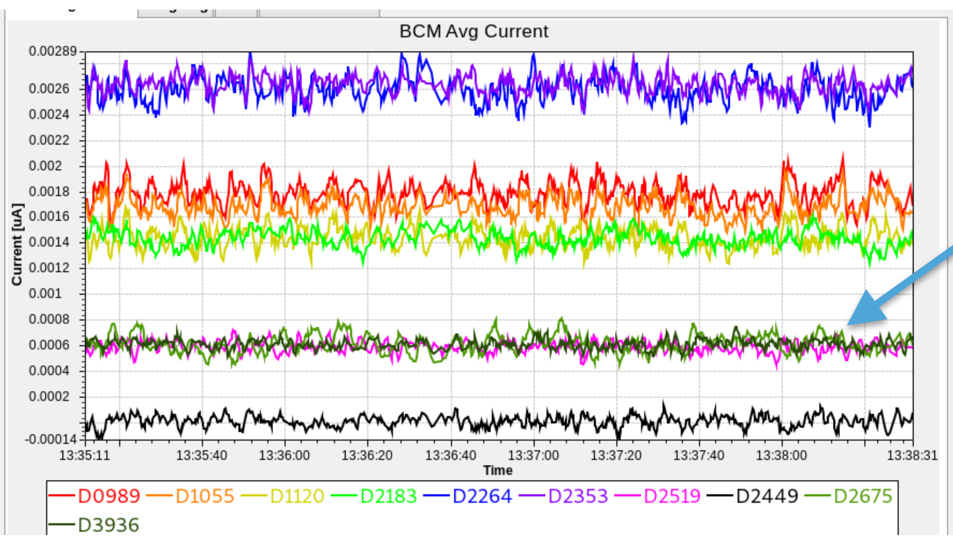
Factor of 2.5 Increase of Beam Intensity with Three Charge States Acceleration

- Simultaneous acceleration of 3 charge states of ^{129}Xe up to 185 MeV/u
- Transmission is 100%

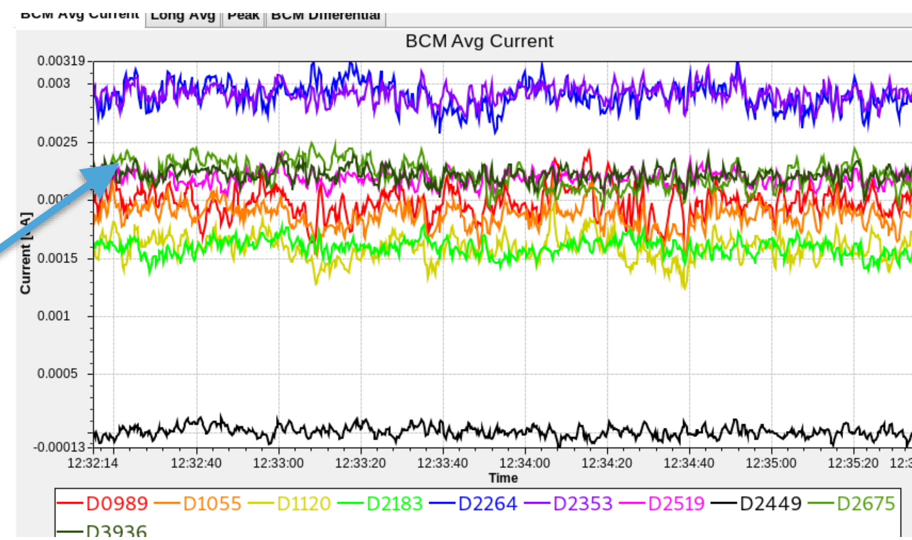
Charge state 50+

Stripping efficiency into 50+ = 30.5%



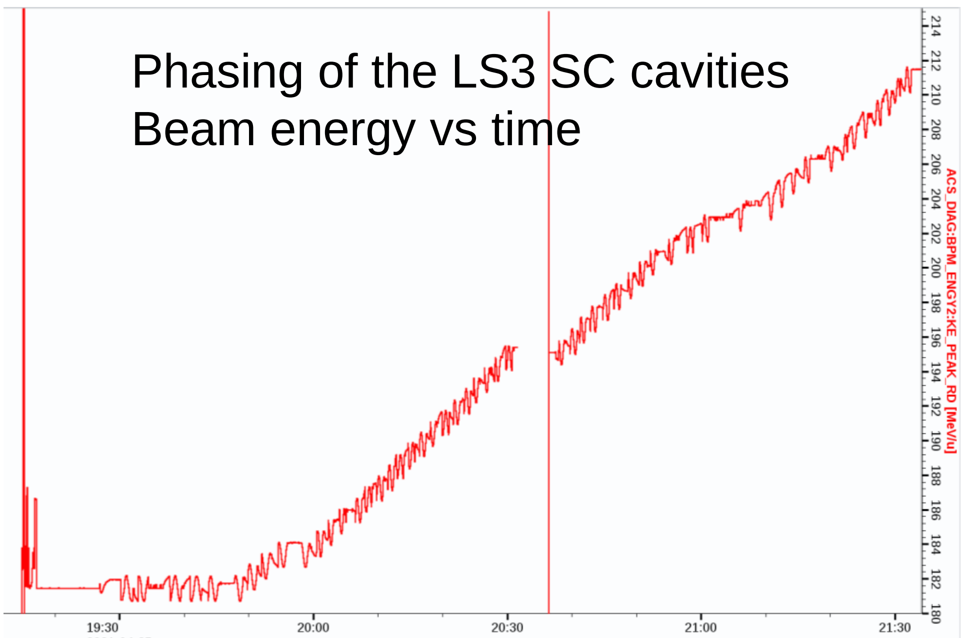
Charge state 49+,50+, 51+

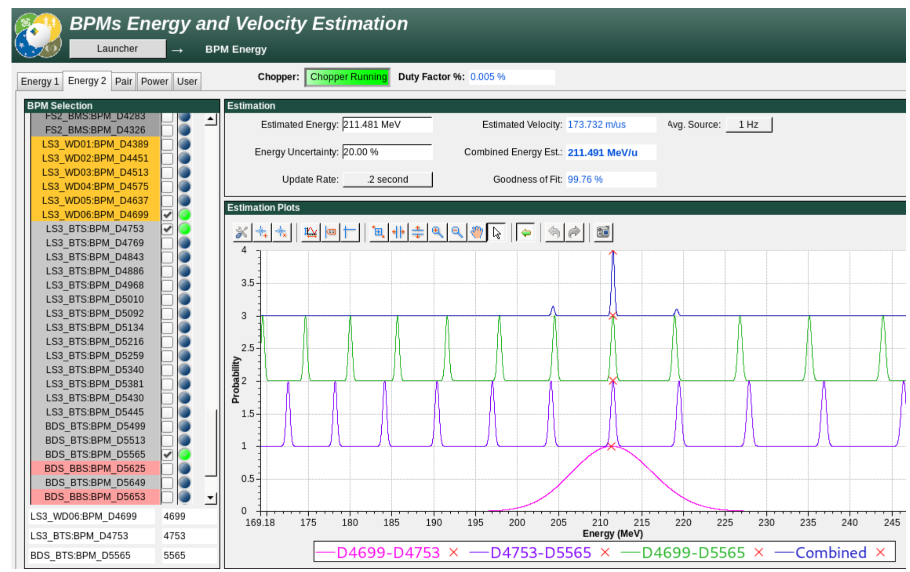
Stripping efficiency into 49+,50+, 51+=76.5%



Krypton and Xenon beams accelerated to 211.5 MeV/u by all 46 Cryomodules

- $^{86}Kr^{34+}$ beam was accelerated to 211.5 MeV/u and delivered to the BDS beam dump both in pulsed (peak current is 1 pμA) and CW modes
- Two-charge state $^{86}Kr^{33+,34+}$ was also accelerated and delivered to the beam dump with 100% transmission and increased intensity by 40%

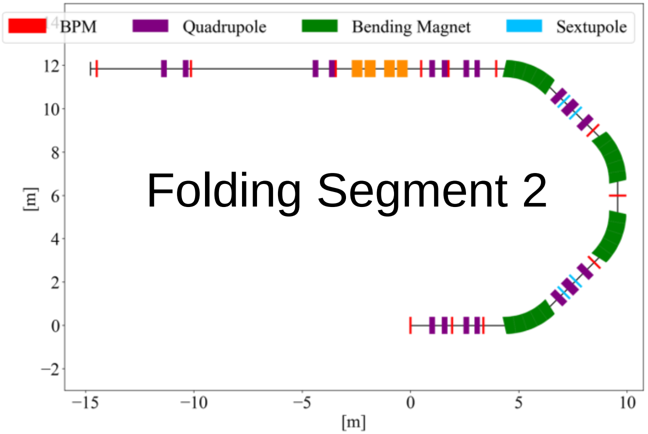


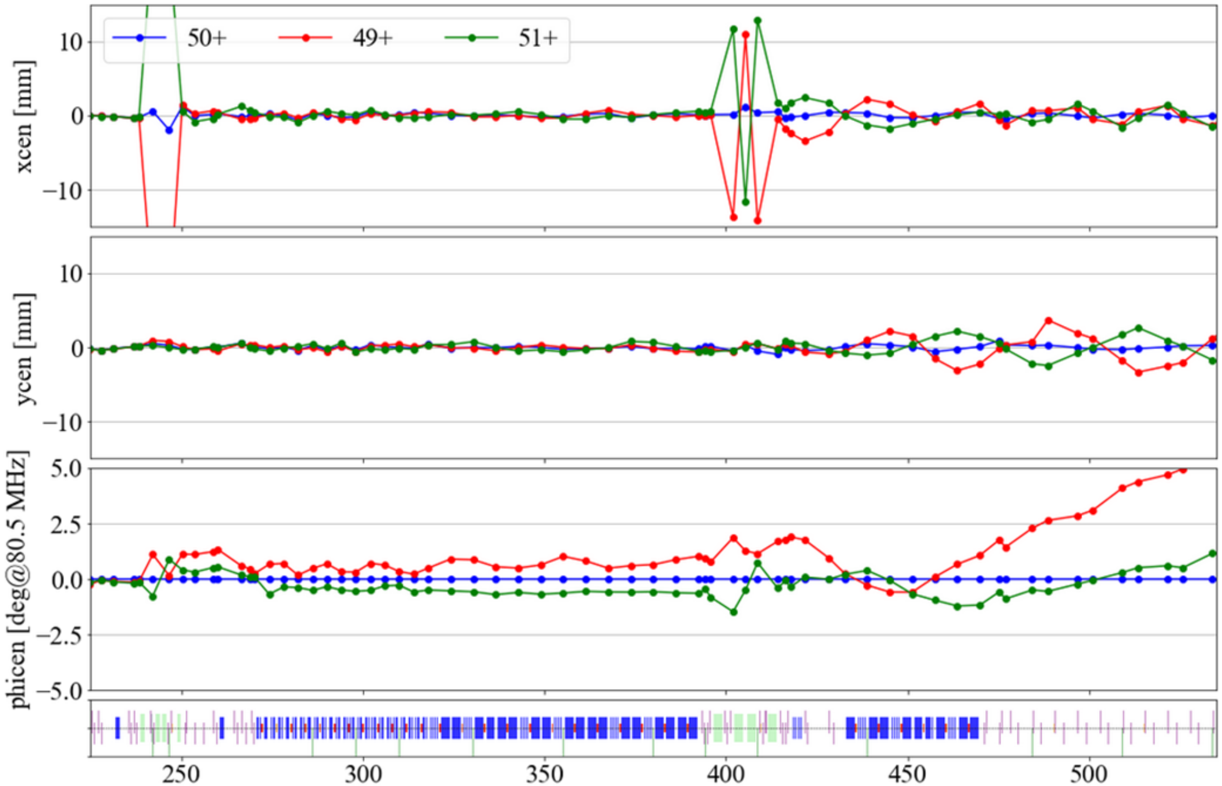


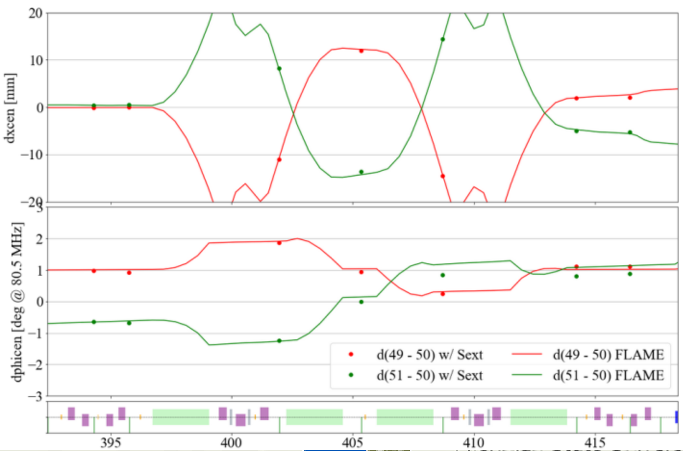
Xenon Beam Acceleration

- Three charge state xenon beam was accelerated to 211.5 MeV/u
- The plots show difference between Xe^{49+} and Xe^{50+}; Xe^{51+} and Xe^{50+}

Second 180-deg bend with SC magnets

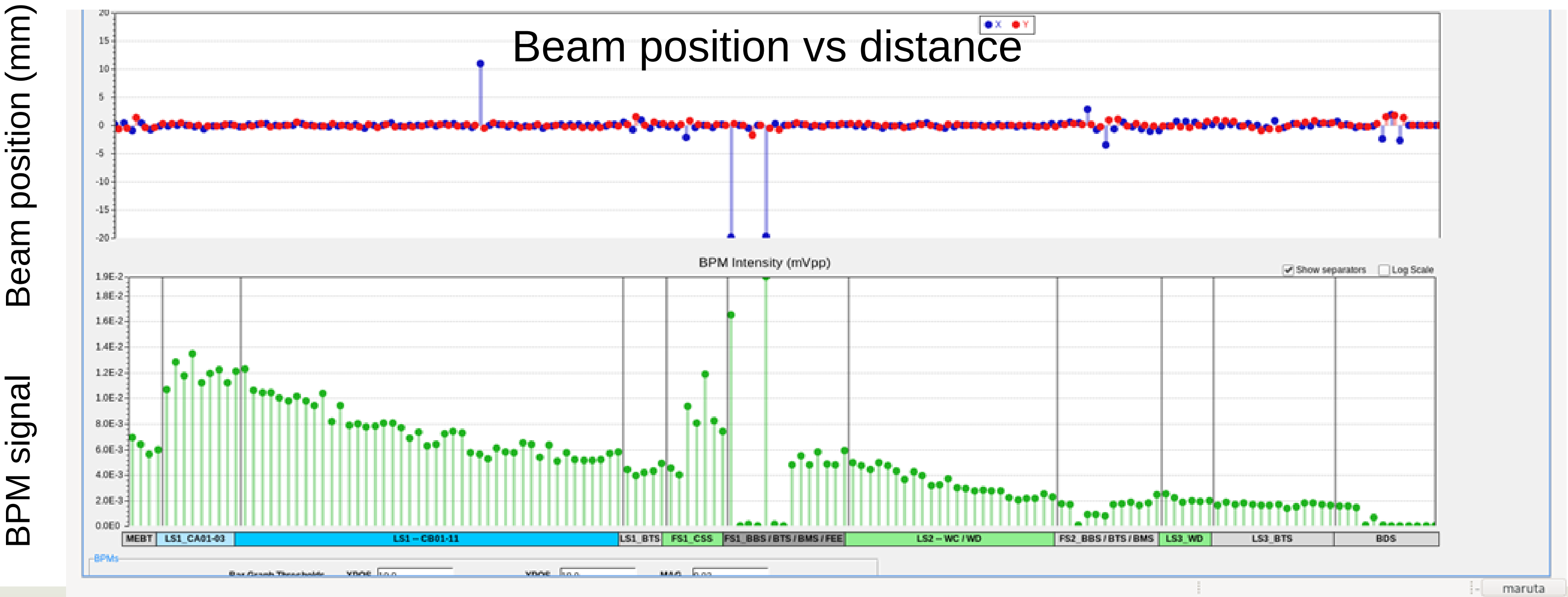






Beam Central Trajectory Correction

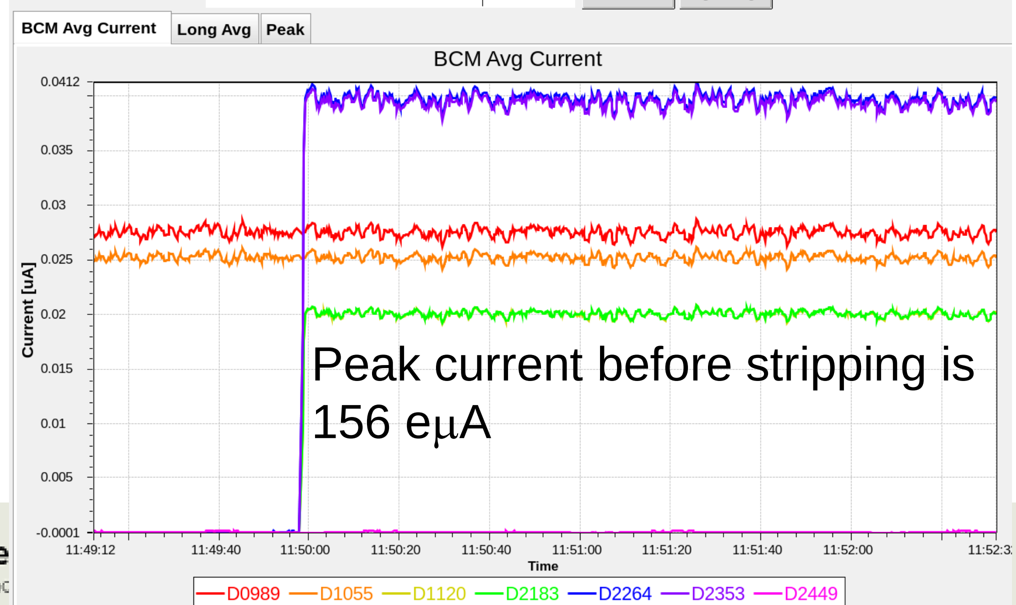
- There are 150 BPMs in the FRIB linac to measure beam positions
  - Renewal frequency is 5 Hz
- High Level Application is based on ORM (Orbit Response Matrix)
  - Response matrix is model based; can be also based on measurements
  - The procedure is applied to ~20 BPM/correctors section by section. Each section tuning time is a couple of minutes



Other Beam Dynamics Aspects

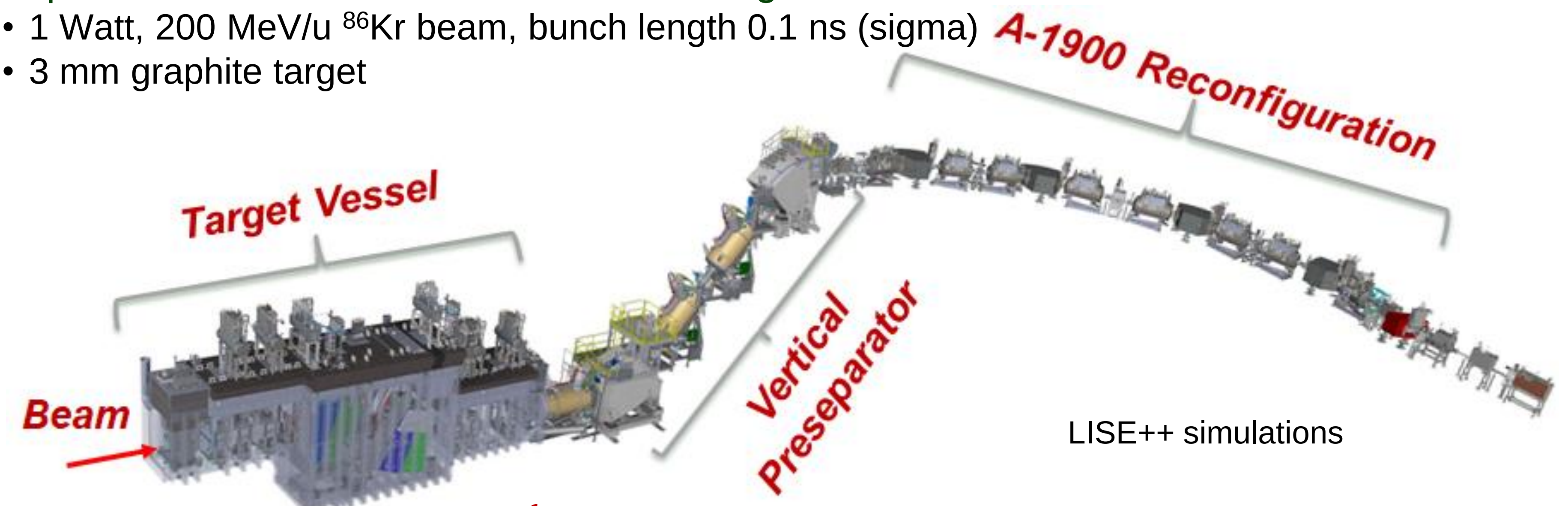
- Using SC solenoids for focusing in long cryomodules
  - There was an extended discussion about 10-15 years ago about the placement of solenoids inside the cryromodules due to concerns of misalignments
  - FRIB proves the concept of long cryomodules
  - SC dipole coils are combined with the solenoid magnet
- Acceleration of 17.5 pμA argon beam demonstrated
  - Equivalent to 200 kW beam on the target in CW mode
- Low beam losses verified in pulsed mode (example with Argonne beam high peak current)
  - No losses in halo monitoring rings

	1 Hz Avg nA		1 Hz Avg uA	Peak Avg	Chan Delay			
FE_LEBT:BCM_D0989	27.878	nA	0.028 uA	215.46 uA	14.20 us	Detail Plot	Engineering	DIAG_MTCA06:BCM4_CH1
FE_MEBT:BCM_D1055	25.475	nA	0.025 uA	197.69 uA	16.30 us	Detail Plot	Engineering	DIAG_MTCA06:BCM4_CH2
FE_MEBT:BCM_D1120	20.197	nA	0.020 uA	156.14 uA	17.00 us	Detail Plot	Engineering	DIAG_MTCA06:BCM4_CH3
FS1_CSS:BCM_D2183	20.197	nA	0.020 uA	155.98 uA	19.80 us	Detail Plot	Engineering	DIAG_MTCA06:BCM4_CH4
FS1_CSS:BCM_D2264	40.113	nA	0.040 uA	318.18 uA	19.10 us	Detail Plot	Engineering	DIAG_MTCA06:BCM5_CH1
FS1_CSS:BCM_D2353	39.796	nA	0.040 uA	315.16 uA	19.20 us	Detail Plot	Engineering	DIAG_MTCA06:BCM5_CH2
FS1_BTS:BCM_D2449	0.029	nA	0.000 uA	0.03 uA	19.80 us	Detail Plot	Engineering	DIAG_MTCA06:BCM5_CH3

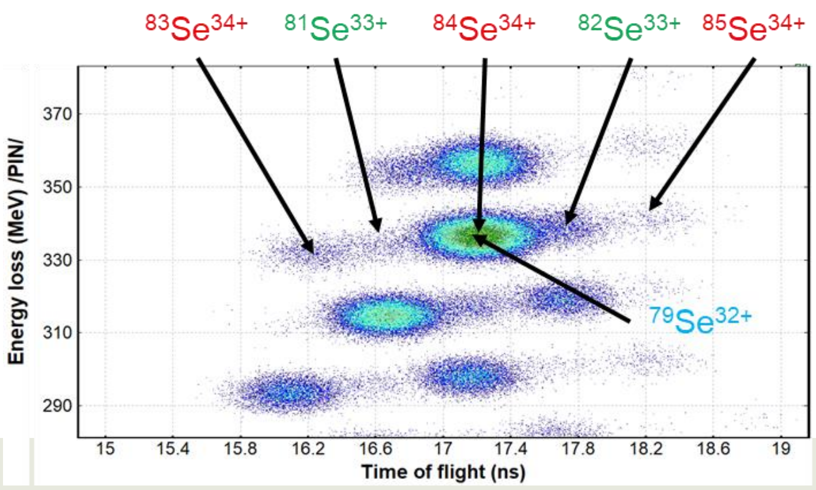


Project KPP: Demonstration of Isotope Production (ARR06)

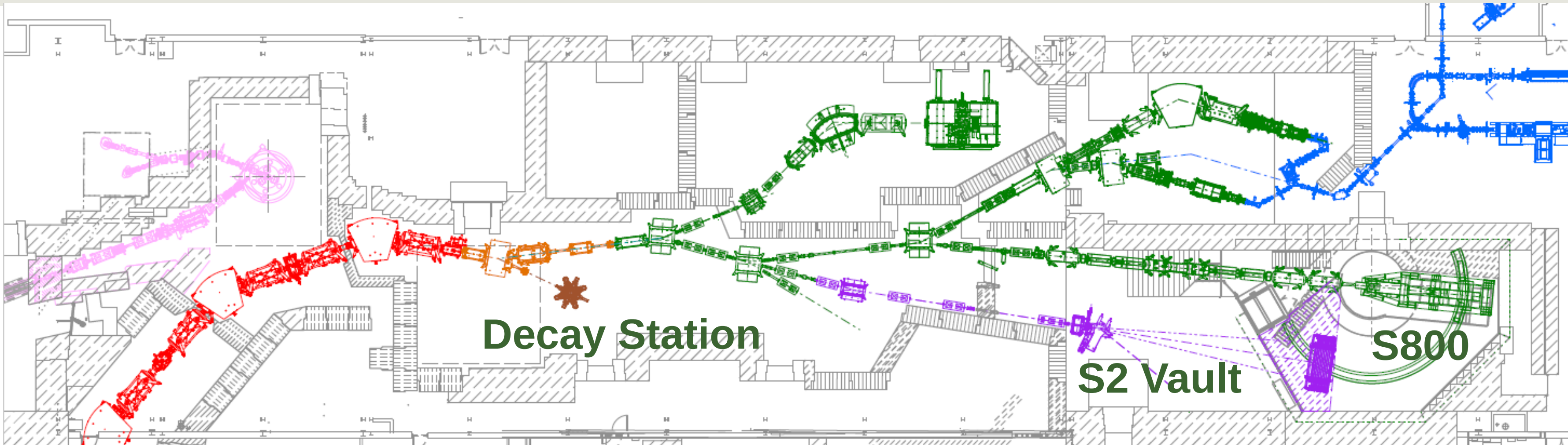
- Separation and identification of ^{84}Se in target hall simulated
  - 1 Watt, 200 MeV/u ^{86}Kr beam, bunch length 0.1 ns (sigma)
  - 3 mm graphite target



LISE++ simulations



ARIS Layout at PAC1 Period



- Commissioning of ARIS and beamline to S800: January 2022
- PAC1 Proposal solicitation
  - 82 proposals submitted
  - FRIB highly supported users with the proposal development
  - Total of 9,784 beam hours are requested
  - The proposals are being reviewed by PAC1

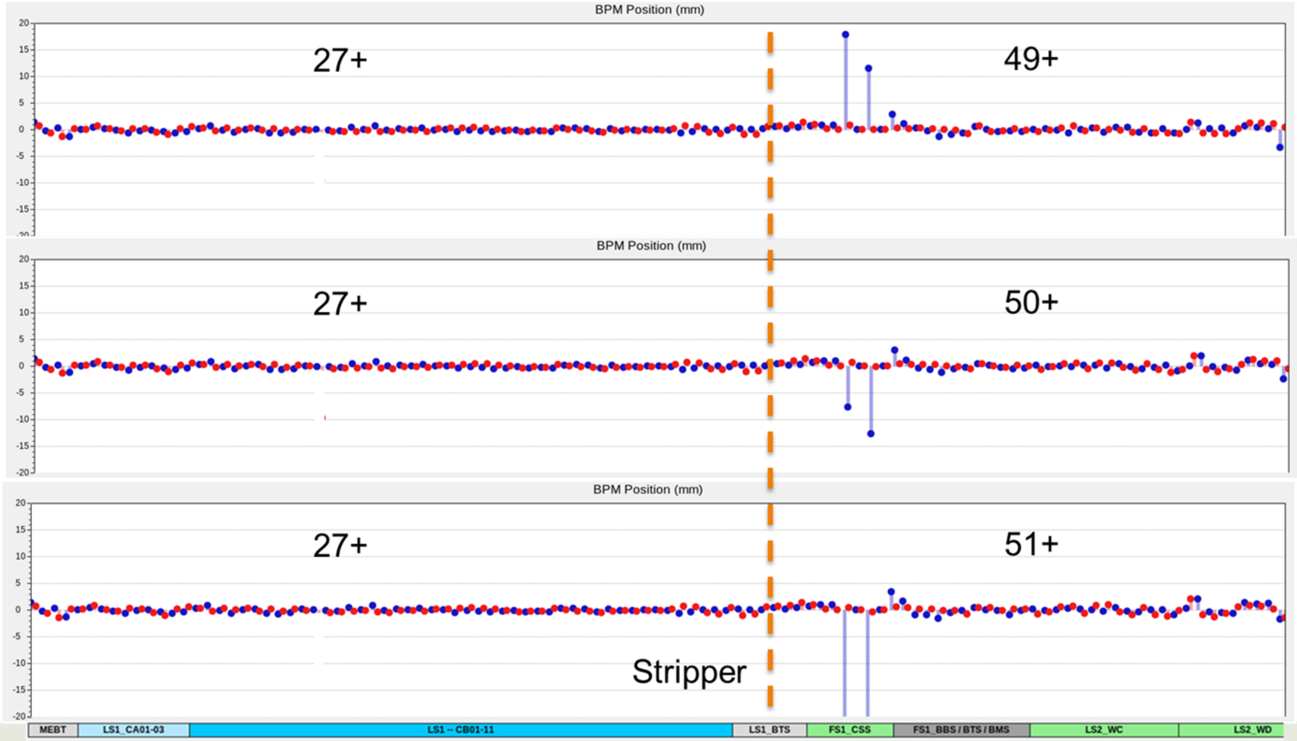
	Abundance (%)	ECR
^{238}U	99.27	✓
^{124}Xe	0.1	✓
^{82}Se	9.4	✓
^{86}Kr	17.3	✓
^{78}Kr	0.35	✓
^{48}Ca	0.19	✓
^{36}Ar	0.33	✓
^{18}O	0.2	✓
^{16}O	99.76	✓

Summary

- FRIB team, in collaboration with many Labs and Universities, succeeded in many accelerator science and technology challenges
- The FRIB project will be completed in January 2022
- User operation starts in FY22
- Next challenges are
  - Beam power ramp up
    - Maintain low beam losses in the linac
    - Safe and reliable operation of target, beam dump and multiple collimators in the target hall
    - High power target and beam dump
  - Provide isotopes per approved experiments with required intensity, purity and high availability of beam time

Multiple Charge State Xe Beam Acceleration

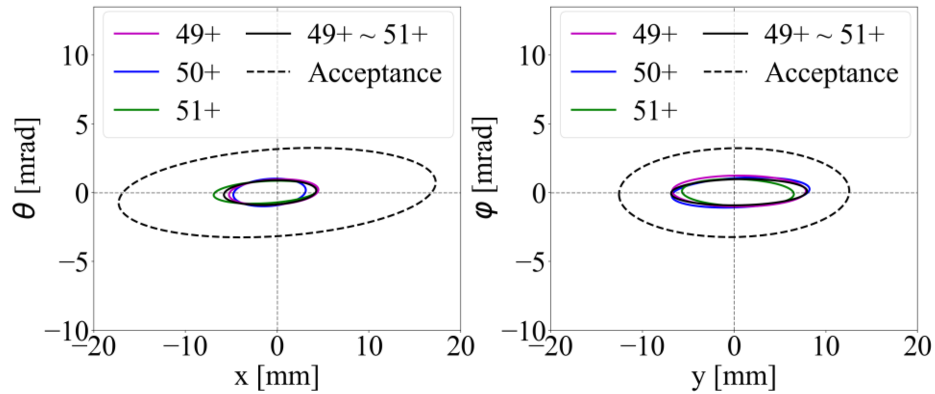
- Three-charge-state Xe beam was successfully accelerated in LS2 up to 180 MeV/u
- First 50+ beam was tuned to set up FS1 and LS2
- These are BPM readings from MEBT to LS2 beam dump



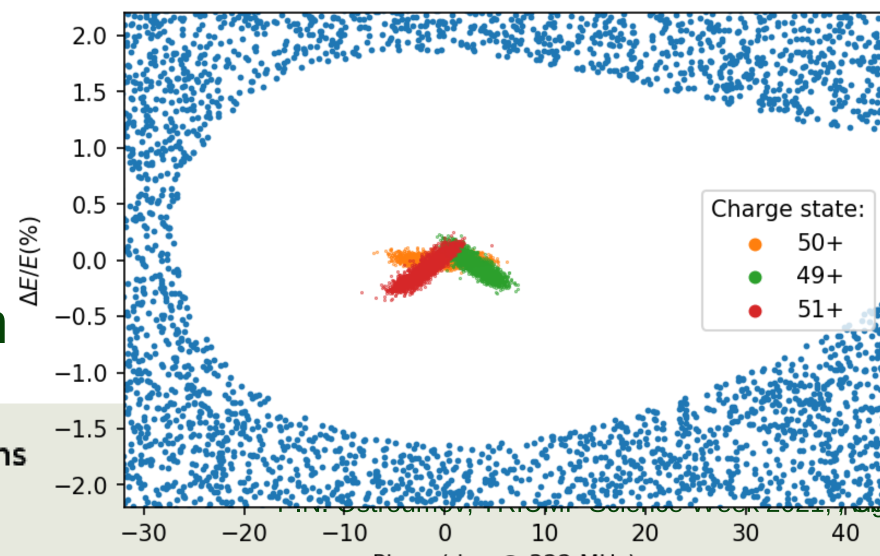
Large Acceptance – Low Beam Losses

- 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



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HLAs

App Name	Function
ALPHA	RF phase tuning
Allison Scanner	Transverse emittance measurement
BETA	Model-based optical element tuning application
Correlation Visualizer	General parameters correlation analysis and visualization application
Device Viewer	Monitor/capture/visualize control variables
ISAAC	Physics model fitting and beam envelope/trajectory reconstruction from measurements
Settings Manager	Manage the physics settings of the accelerator system
Trajectory Correction	Optics response matrix (physics or online model) based trajectory correction app
Trajectory Viewer	Beam trajectory visualization app
Lattice Viewer	Present lattice device info segment by segment, layout visualization
Online Model	Online simulator with FLAME for the LINAC
Physics Calculator	Quickly checking physics parameters and plot trends
Virtual Accelerator	Start/stop virtual accelerators for application development
Wire Scanner App	Operating wire-scanner device and do data processing for beam position and size
Unicorn App	Manage and visualize the scaling laws between engineering and physics units
Synoptic View & Control	Another novel way to visualize and control the accelerator facility
MHB Tunner	Plot the RFQ longitudinal acceptance and beam phase-space for multi-harmonic tuning
PM Viewer	Inspect and control a list of wire-scanner devices
Energy Gain Calculator	Calculate the ion energy gain within a cavity
BPM Plot	Show/save/load BPM readings
BPM Averaging	Average BPM readings
Achromat Tuning	Data analysis for achromat tuning