FRIB Beam Commissioning

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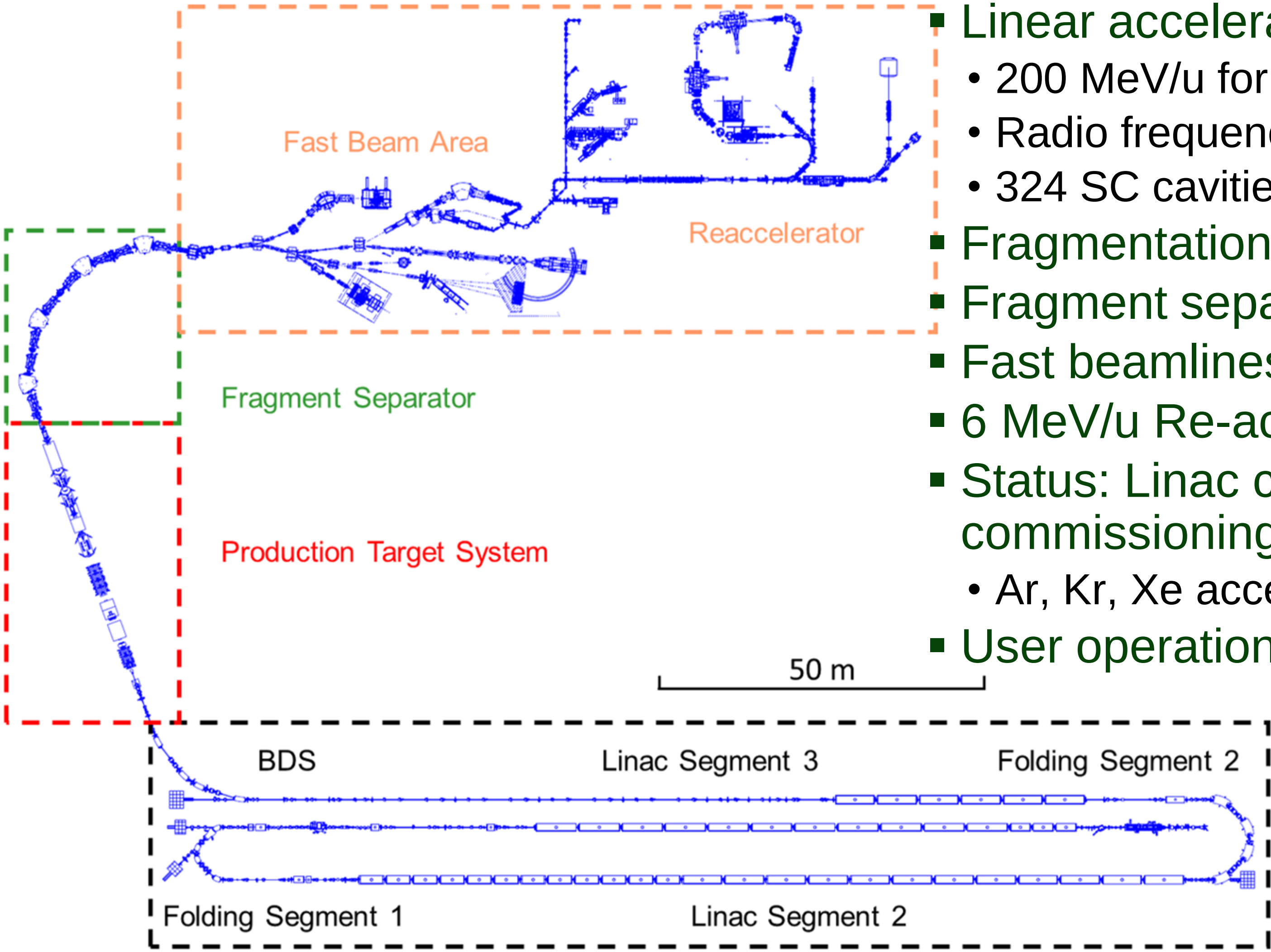
FRIB Layout



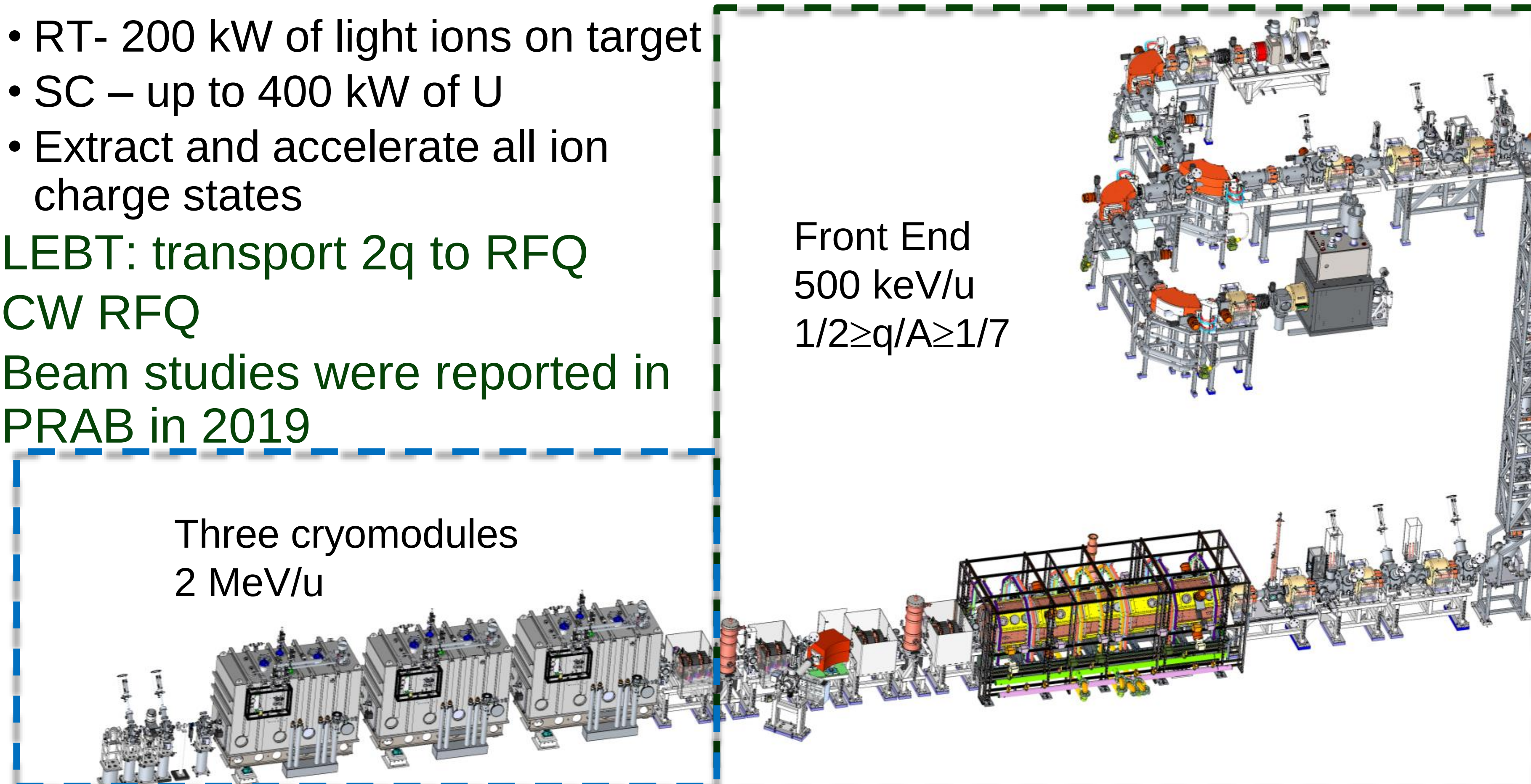
- Linear accelerator
  - 200 MeV/u for uranium
  - Radio frequency quadrupole
  - 324 SC cavities in 46 cryomodules
- Fragmentation target
- Fragment separator
- Fast beamlines
- 6 MeV/u Re-accelerator
- Status: Linac construction and commissioning is complete
  - Ar, Kr, Xe accelerated to 212 MeV/u
- User operation starts in May 2022

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

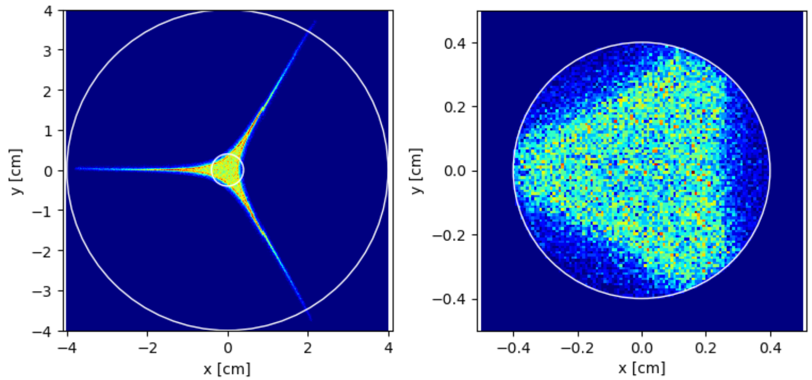
FRIB Linac Beam Commissioning Stages

- 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



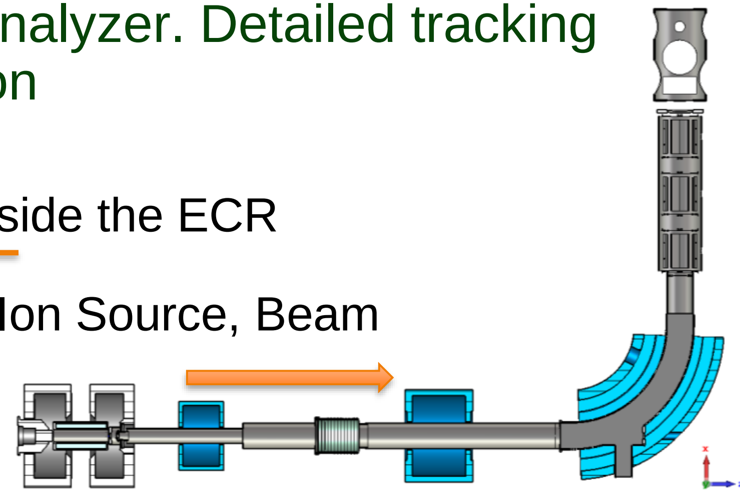
Simulations and Beam Matching in Upper-LEBT

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



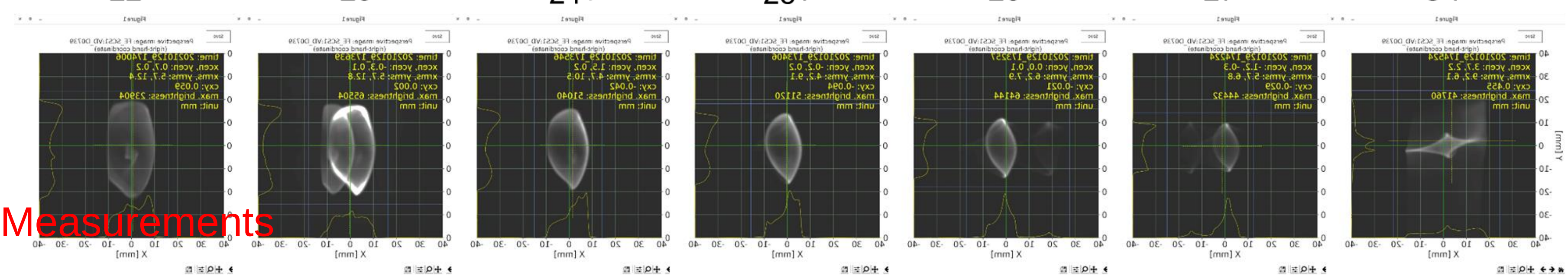
Tracking inside the ECR

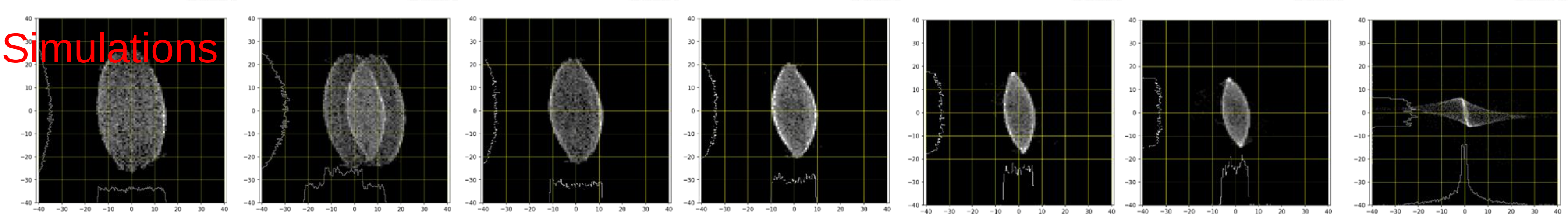
ECR Ion Source, Beam



Xenon beam

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

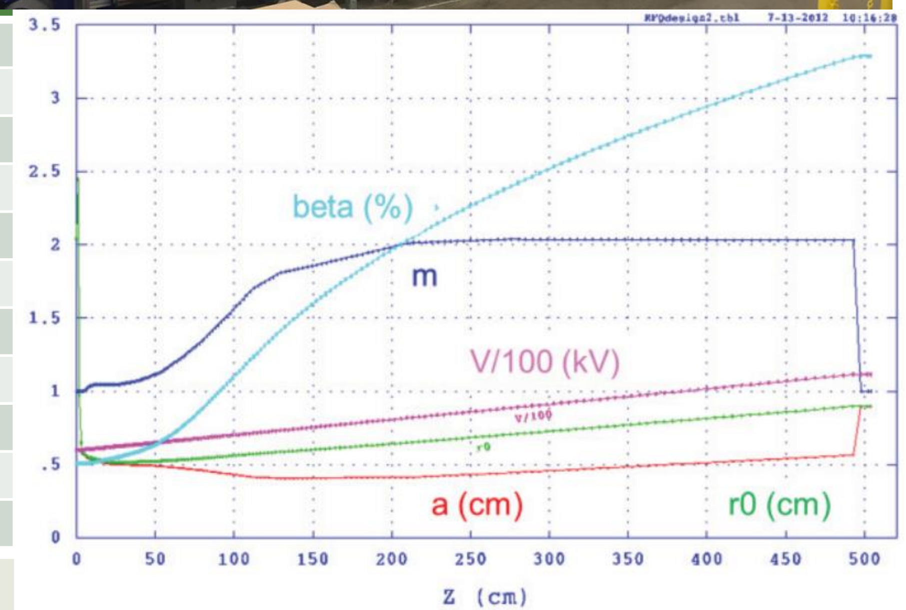




Radio Frequency Quadrupole

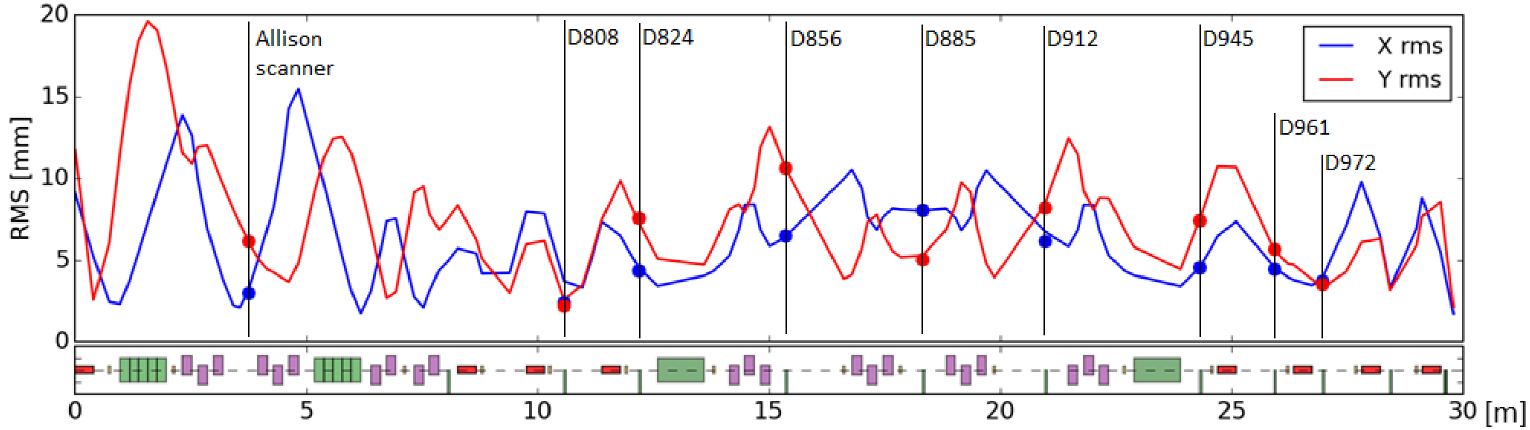
- Unique parameters:
  - CW
  - Maximum voltage is 112 kV
  - Variable R_0 and voltage
  - q/A=1/7
- Conditioned at the design voltage
  - Tested with uranium beam

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

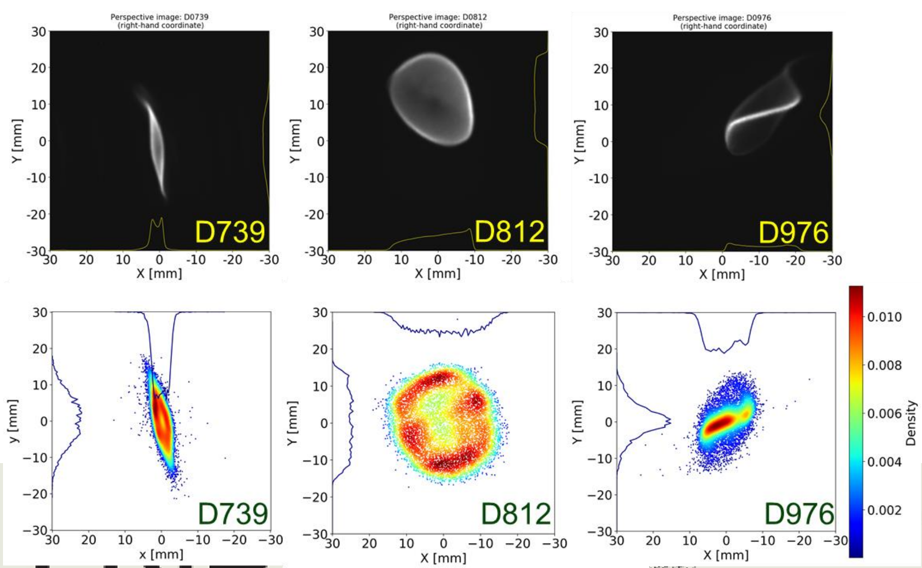


Low Energy Beam Transport

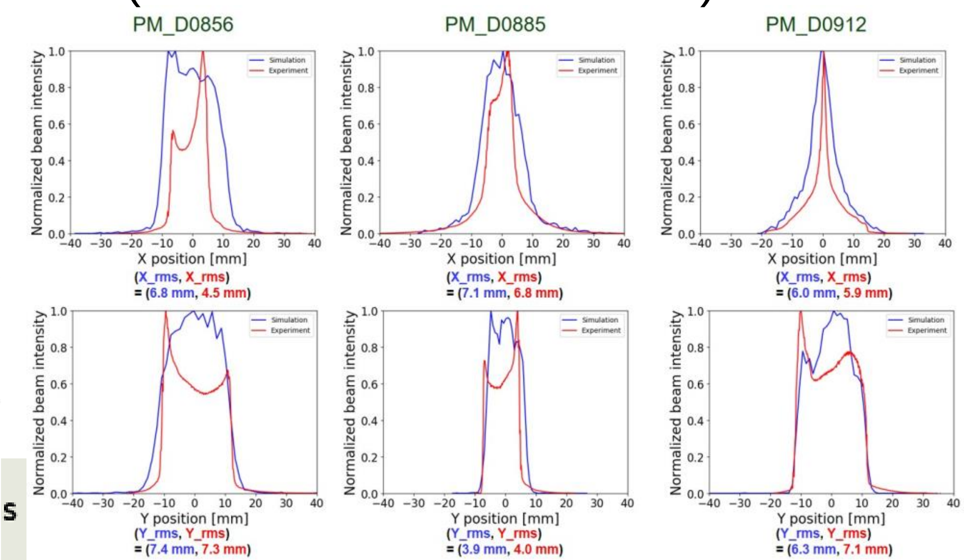
- Typical envelopes of the beam in the LEBT



Viewer images and TRACK simulations

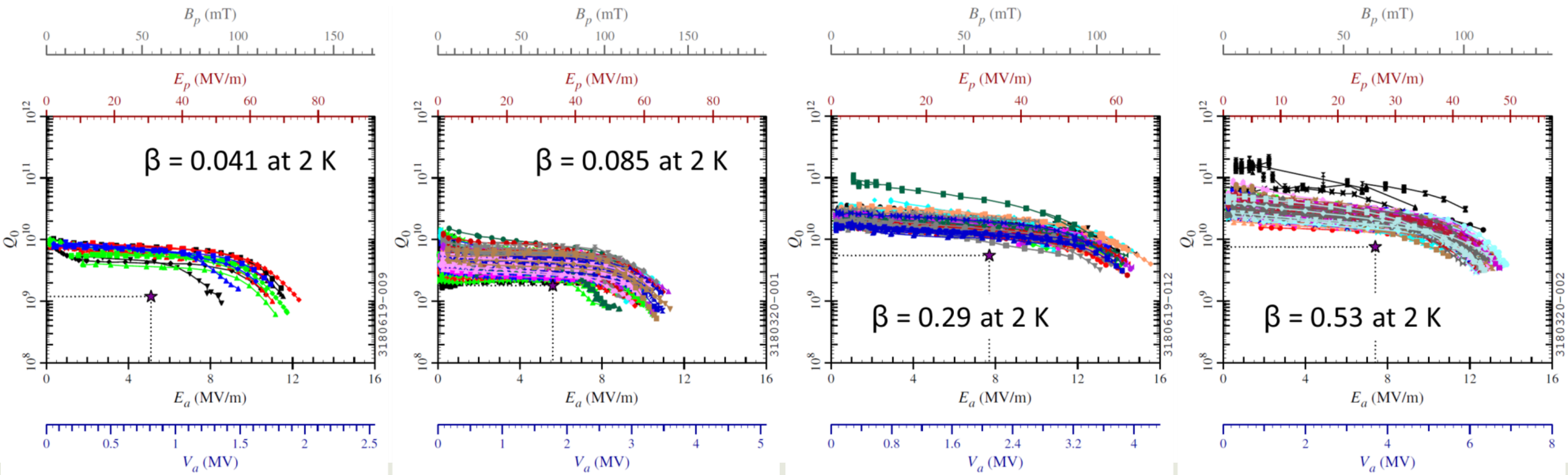


Beam profiles along the LEBT (measured and simulations)



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



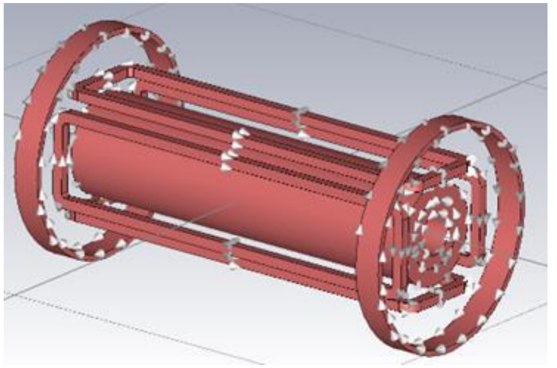
SRF Cryomodules

Example of cryomodules' cold mass

$\beta = 0.53$

$\beta = 0.085$

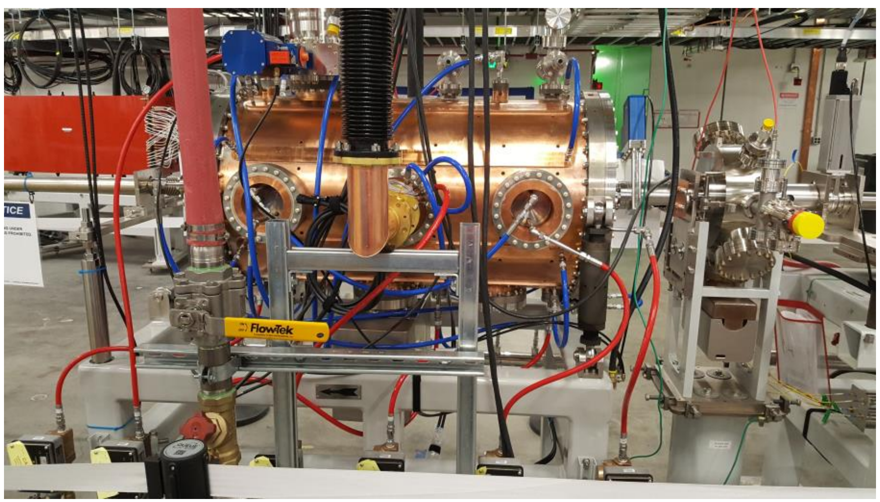
Cryomodules include SC magnet assembly of solenoid and dipole coils



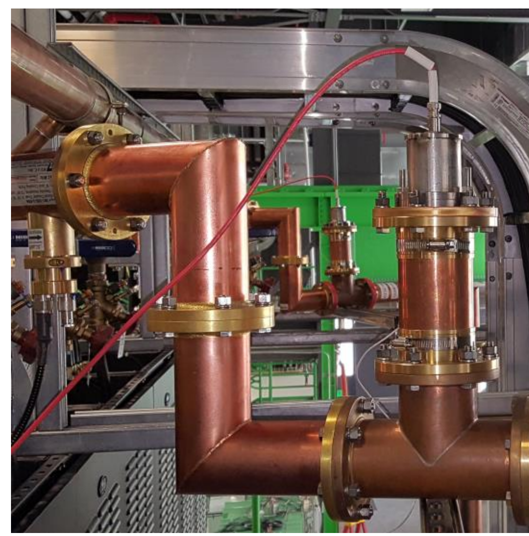
All 46 cryomdules installed in the tunnel

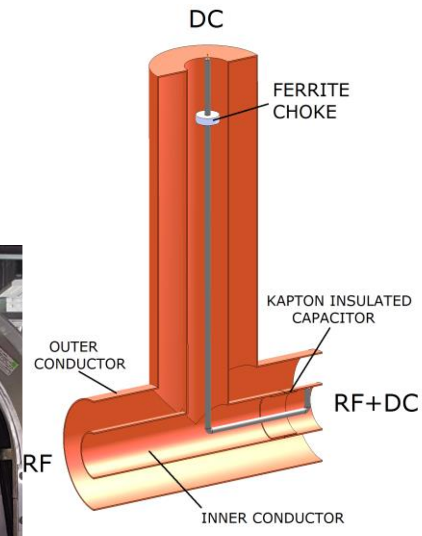
Selected Innovations

- 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



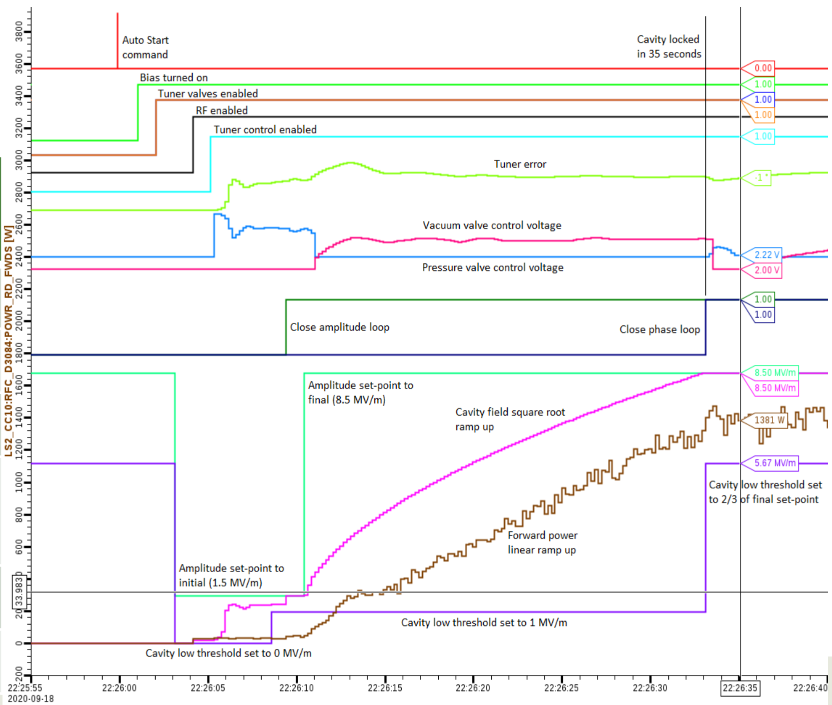


Auto-Start of Resonators

- 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

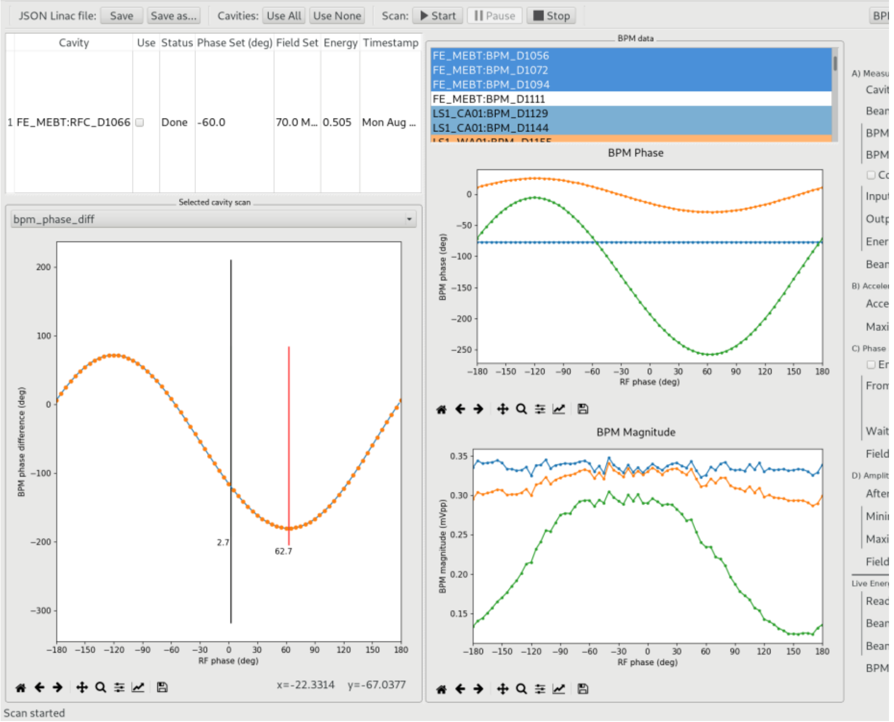


High-level Physics Controls is Routinely Used to Enhance Machine Availability

- Currently there are 25 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, BETA
  - Instant Phase Setting (IPS)
  - Trajectory correction with ORM
  - Viewer image processing
- ALPHA: automated phasing of FRIB RF cavities
  - 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 screen

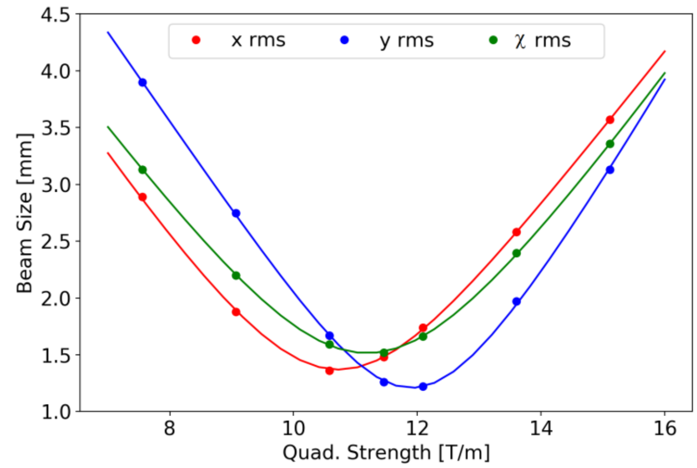
Phase scan: vary cavity phase and detect bunch phase with BPPM

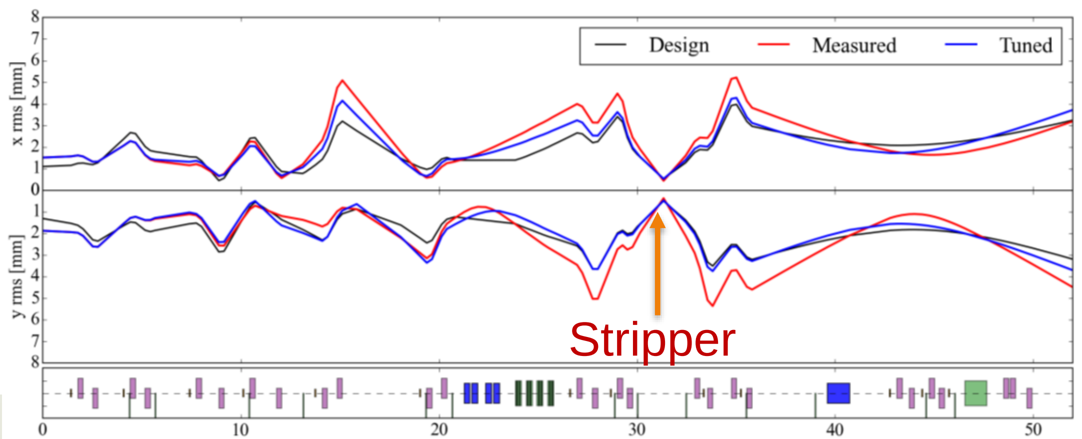


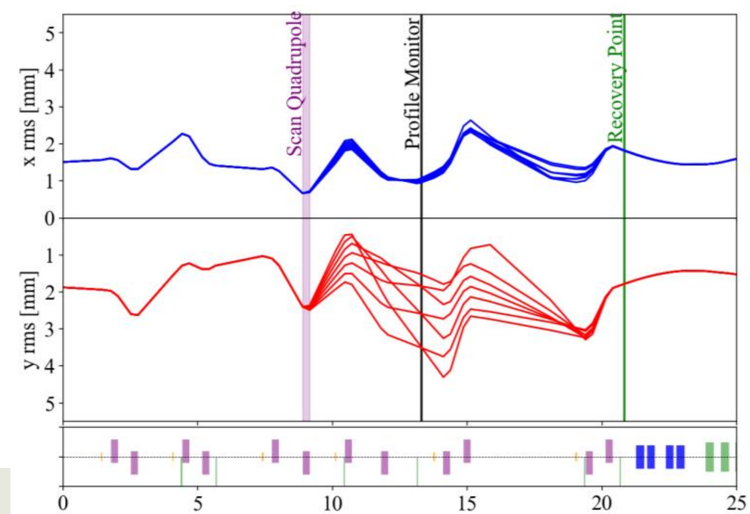
- Python-based HLAs are extremely useful for quick machine settings and will be updated for user-friendly use by operators

Typical Beam Parameters in Linac Segment 1

- Beam parameters have been measured in LS1
  - Longitudinal emittance at 2 MeV/u
  - Transverse emittance at 17 and 20 MeV/u
- Quadrupole scan and profile measurement
- Beam size on the Li stripper should be 0.5 mm rms or smaller
- We will use rotating carbon target initially for beams <10 kW on target

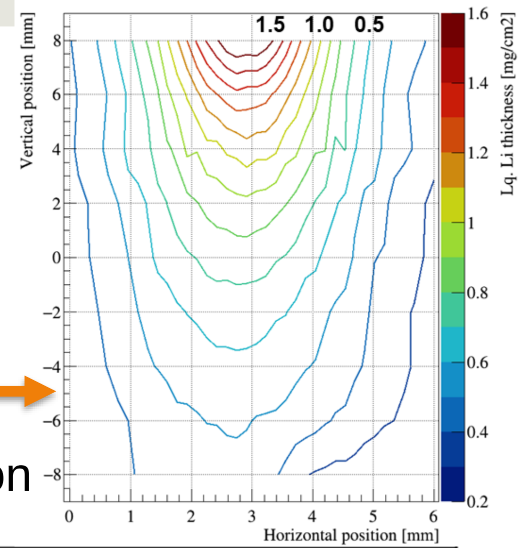






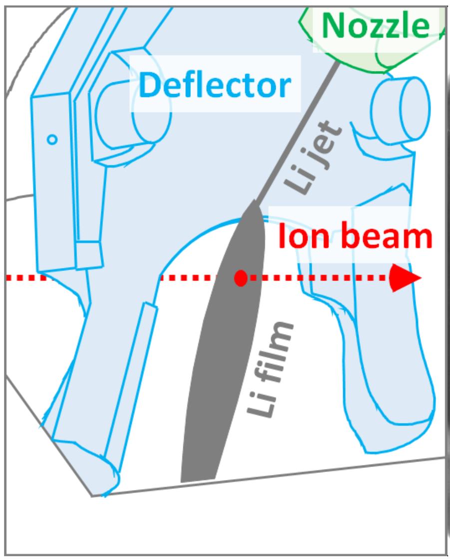
Liquid Lithium Charge Stripper Tested with Ar, Xe and U beams

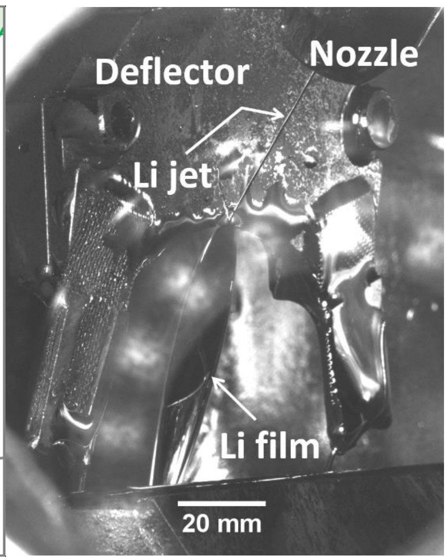
- Tested with 17 and 20 MeV/u Ar, Xe and U beams
- Tested with 10 pμA pulsed argon beam
  - Average beam power was limited by 500 W beam dump
- The film thickness
  - 1 mg/cm^2 for Xe and Ar beams
  - 1.4 mg/cm^2 for U

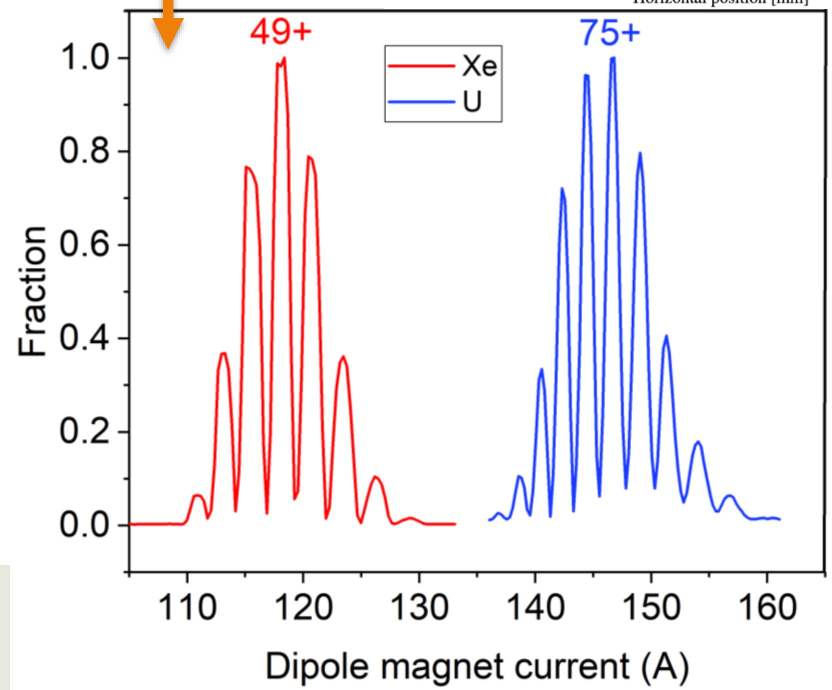


Li film thickness

Charge distribution



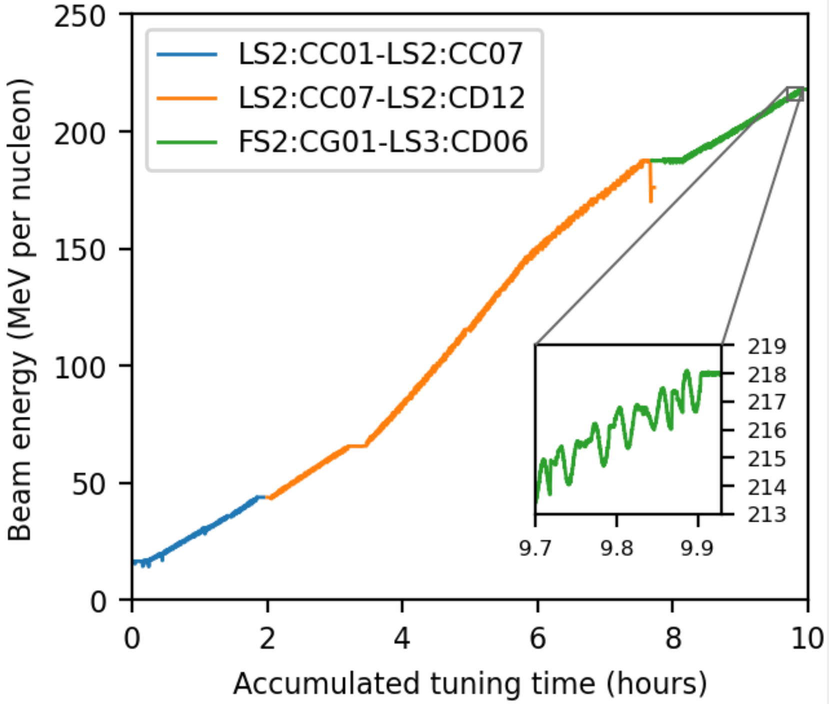




^{36}Ar, ^{86}Kr and ^{129}Xe Accelerated above 200 MeV/u

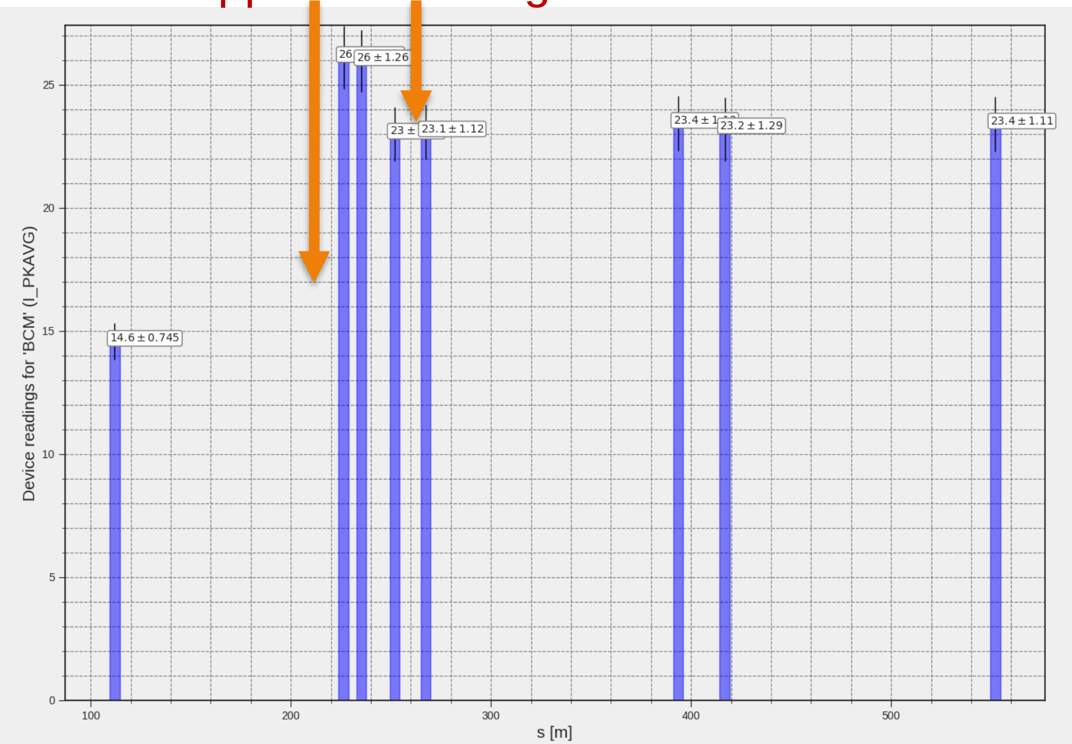
- Three-charge-state $^{124}Xe^{49+,50+,51+}$ and two-charge state $^{86}Kr^{33+,34+}$ were also accelerated and delivered to the beam dump with 100% transmission

Phasing of SC cavities
Beam energy vs time



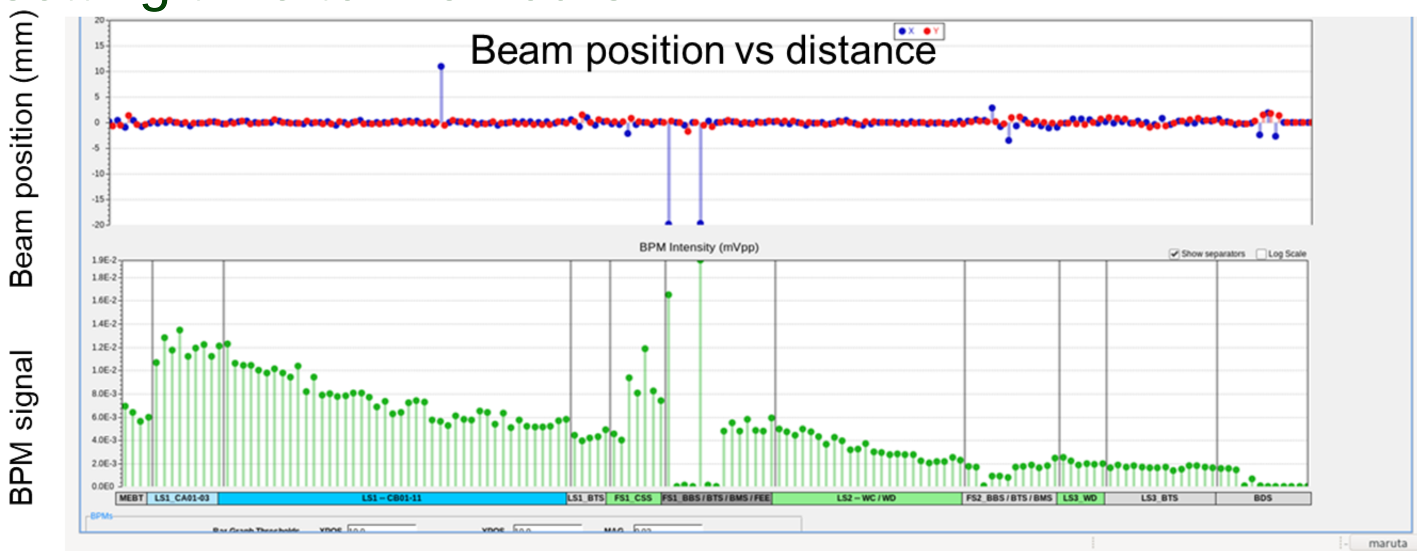
Transmission of ^{36}Ar, beam current in μA

Stripper   Charge Selector



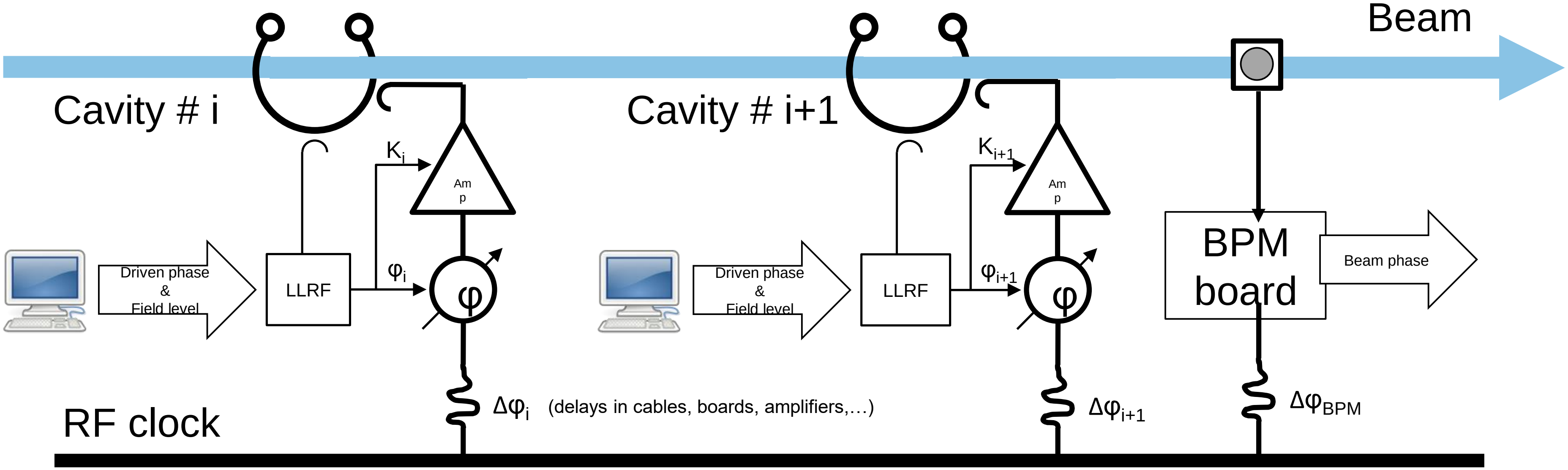
Model-Based Beam Central Trajectory Correction

- 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 2-3 hours



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

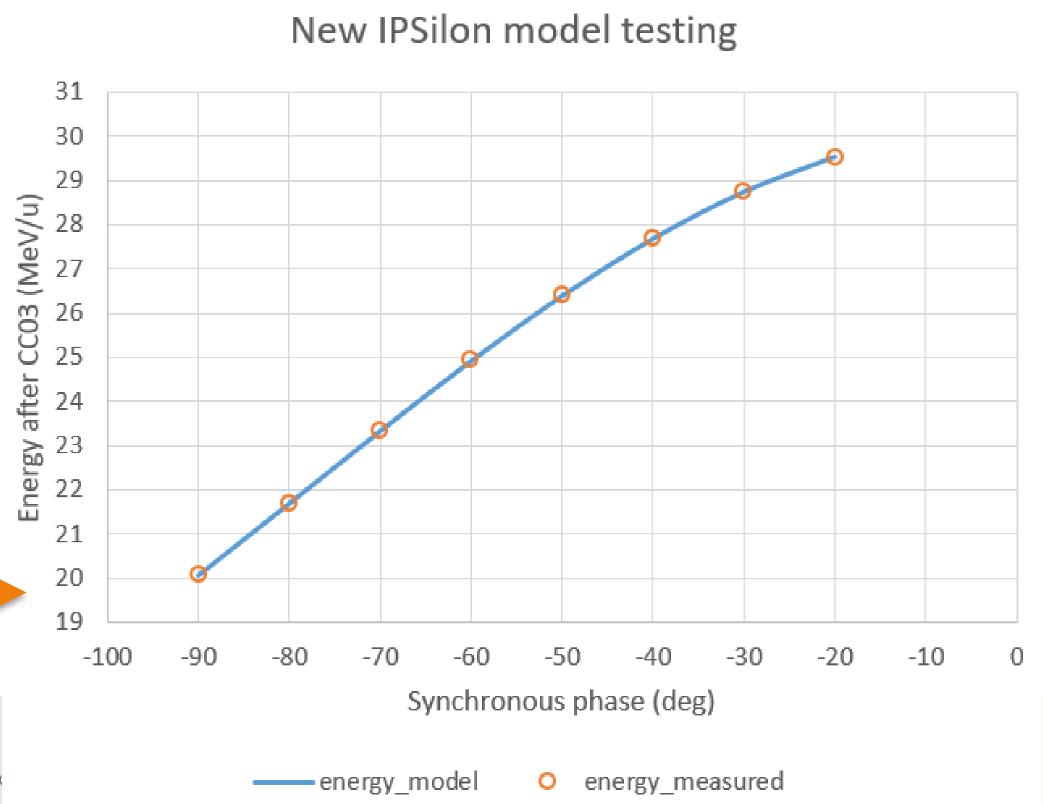
$$\begin{cases} \dfrac{dW}{dz} = qE_z(z) \\ \dfrac{dt}{dz} = \dfrac{1}{v_z} \end{cases}$$

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

Model-Based Instant Setting of Phases and Amplitudes for Linac Segments

- Static phase shifts in Radio Frequency (RF) transmission/amplifier lines and Beam Position Monitor (BPM) cables were calibrated by the beam which energy is known with high accuracy, $\delta E/E=10^{-4}$
- The model calculates phase and amplitude setting for any given ion species to reach specified energy
- Instant phase/amplitude model-based setting was applied to all linac segments
- This application allows us to set each section of the linac within a minute
- Can be applied for instant retuning around failed cavities

Demonstration of IPS: measured and modeled beam energies for various synchronous phases in LS2



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%

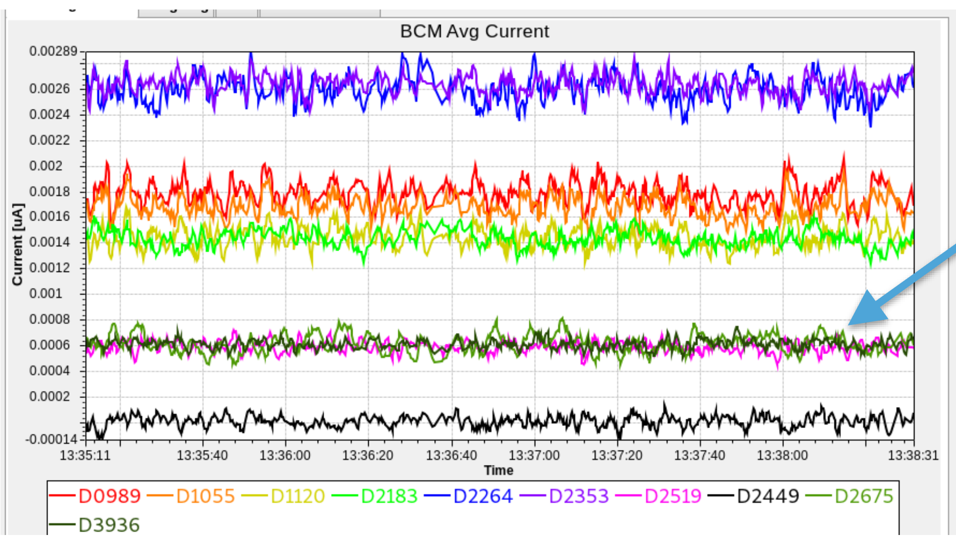
Charge state 50+

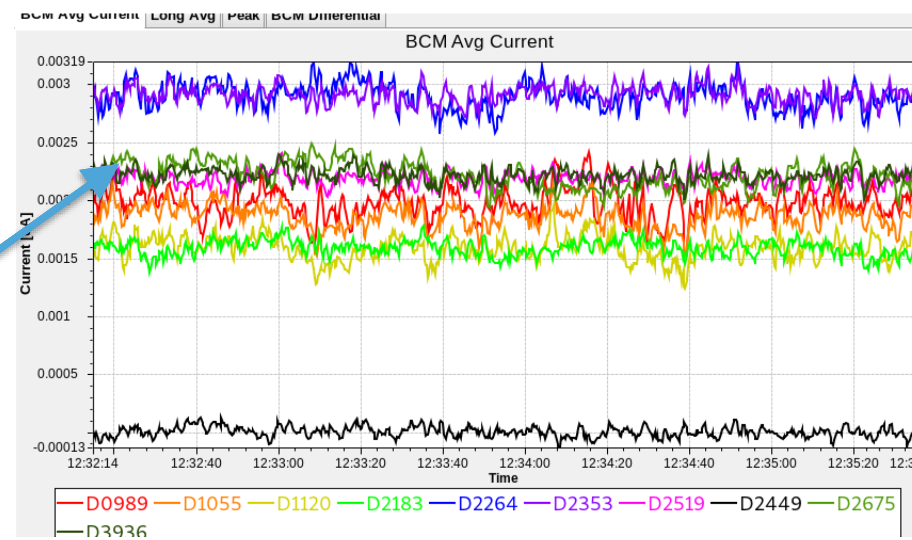
Stripping efficiency into 50+ = 30.5%

49+=23%

Charge state 49+,50+, 51+

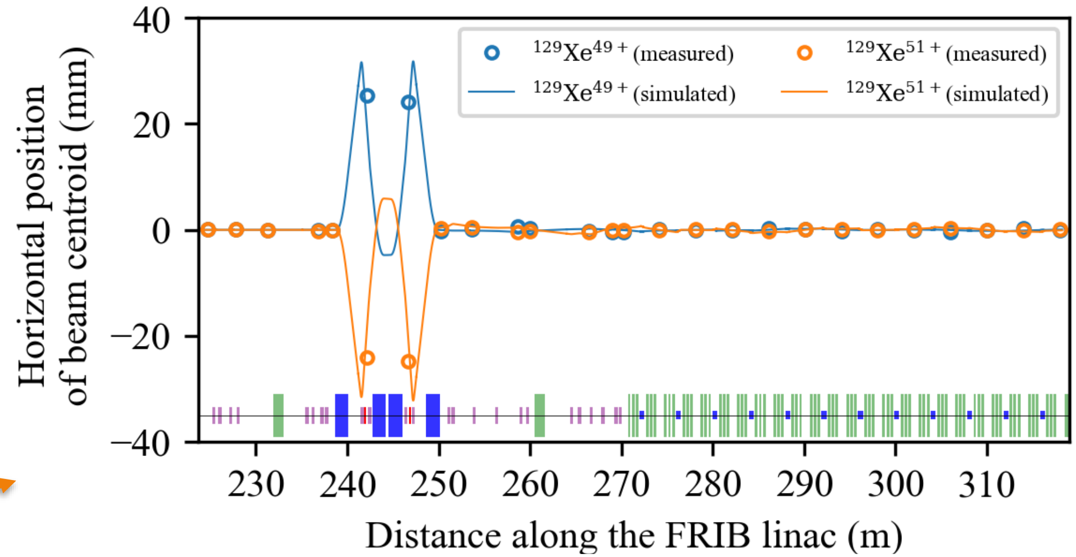
Stripping efficiency into 49+,50+, 51+=76.5%

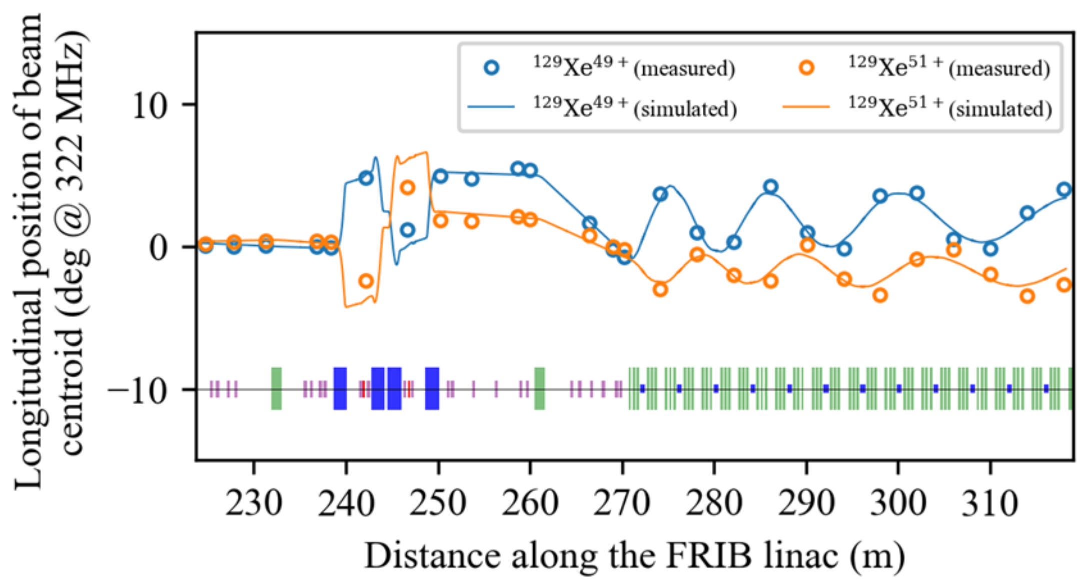


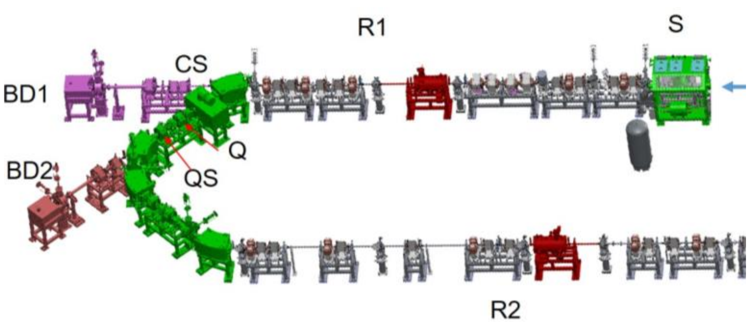


Measured and Simulated Multi-q Beam Parameters Nearly Identical

- 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



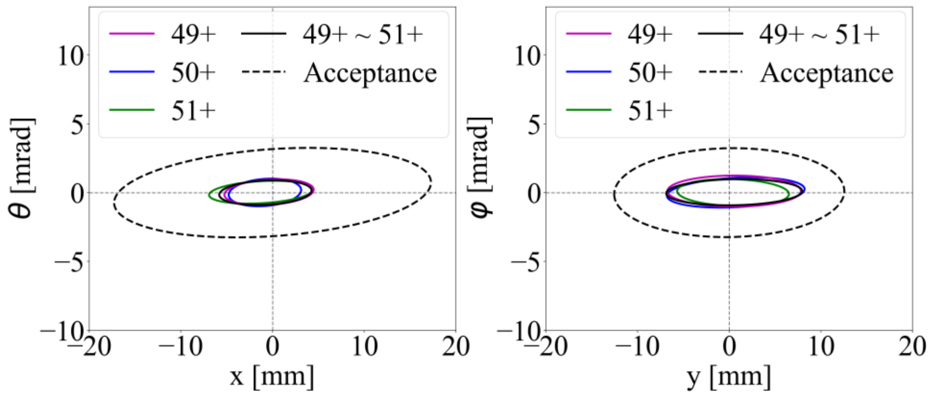




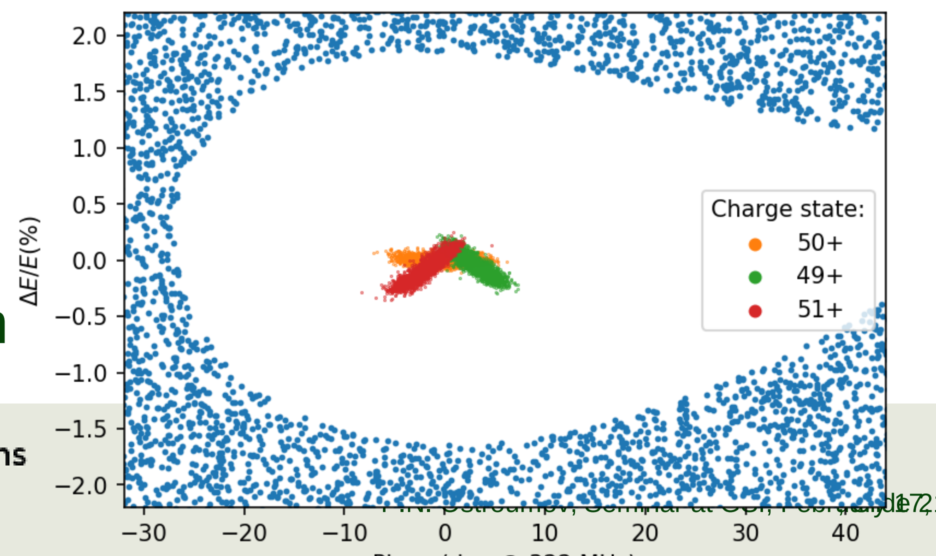
Large Acceptance – Low Beam Losses

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



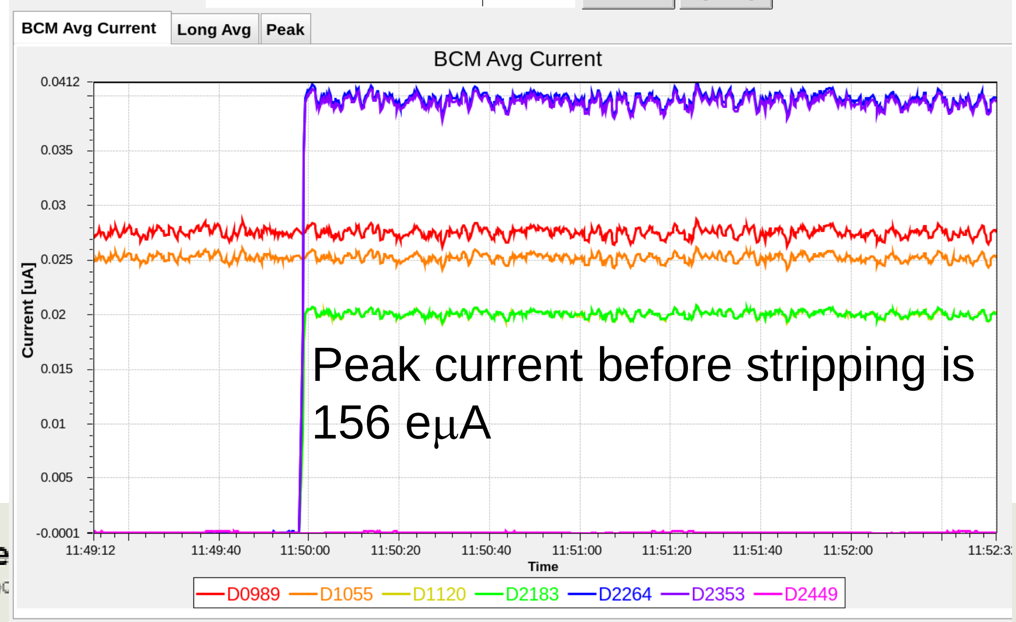
Longitudinal phase space images of three -charge-state Xe and the linac acceptance



Some Beam Dynamics Aspects

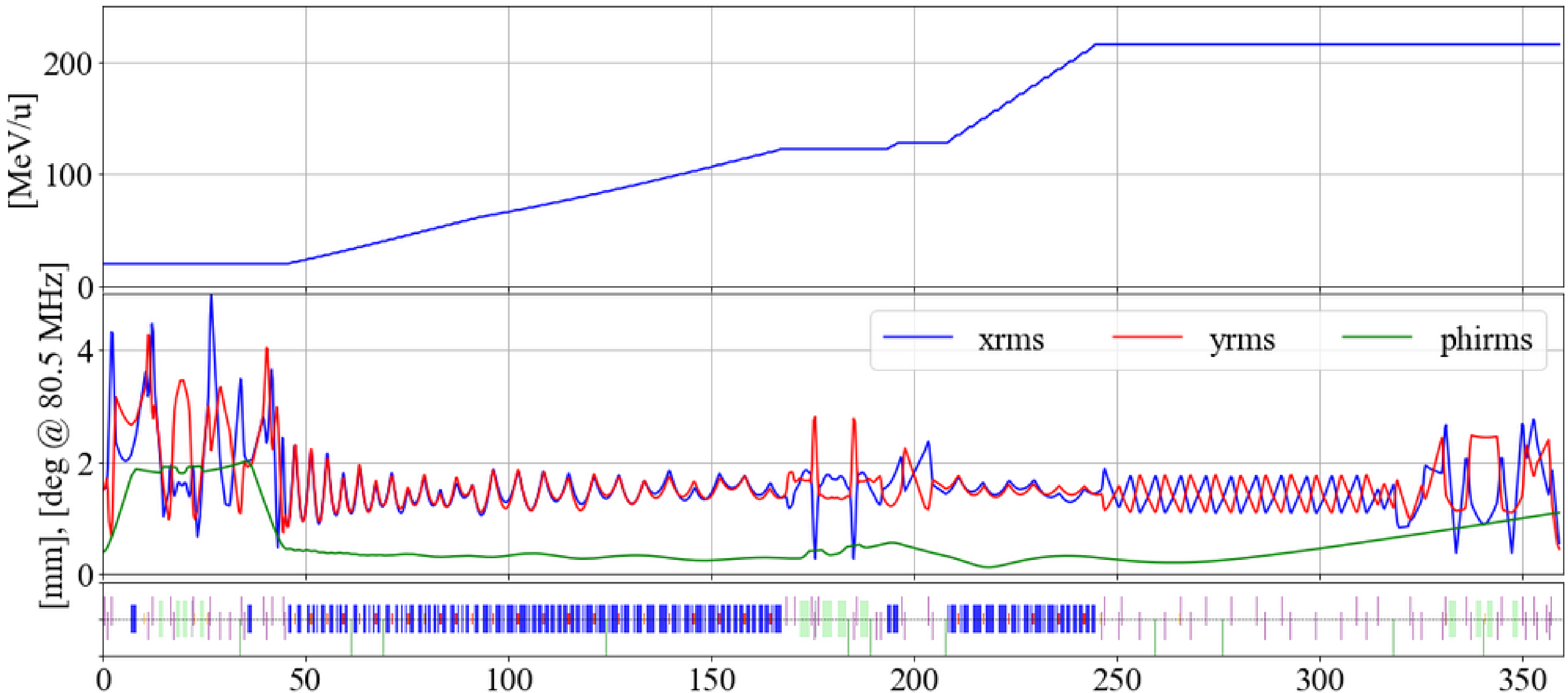
- Using SC solenoids for focusing in long cryomodules
  - There was an extended discussion about 10-15 years ago about the placement of solenoids inside the cryromodules due to concerns of misalignments
  - FRIB proves the concept of long cryomodules
  - SC dipole coils are combined with the solenoid 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



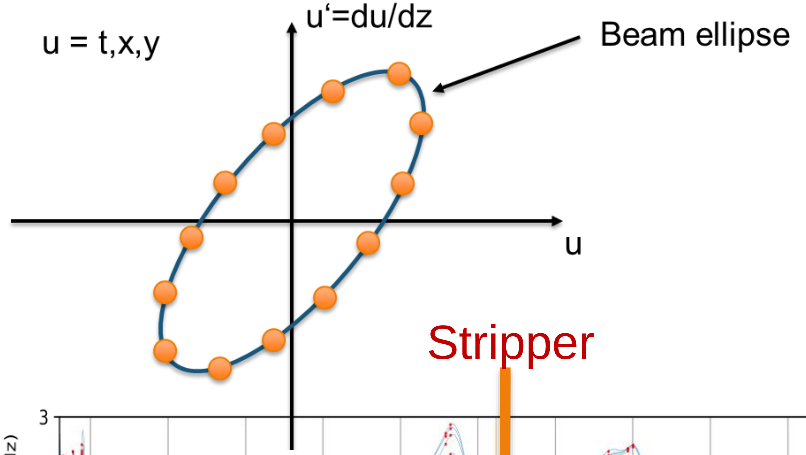
3D Computer Model Setting is Applied for Entire Linac

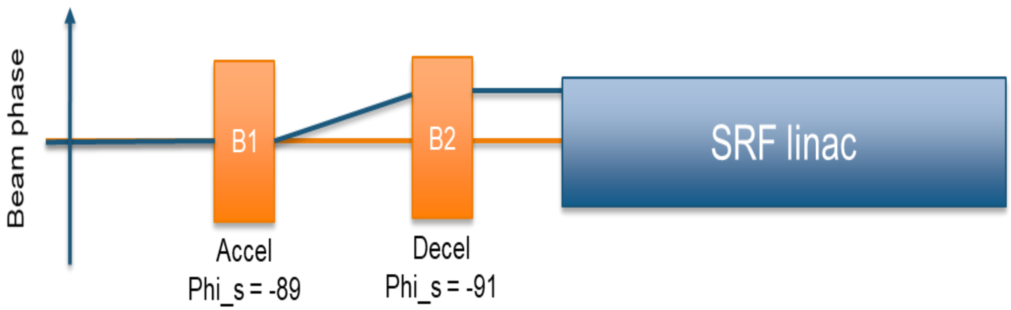
- 210 MeV/u ^{36}Ar tune for ARR07
- Measured beam parameters are consistent with the simulations

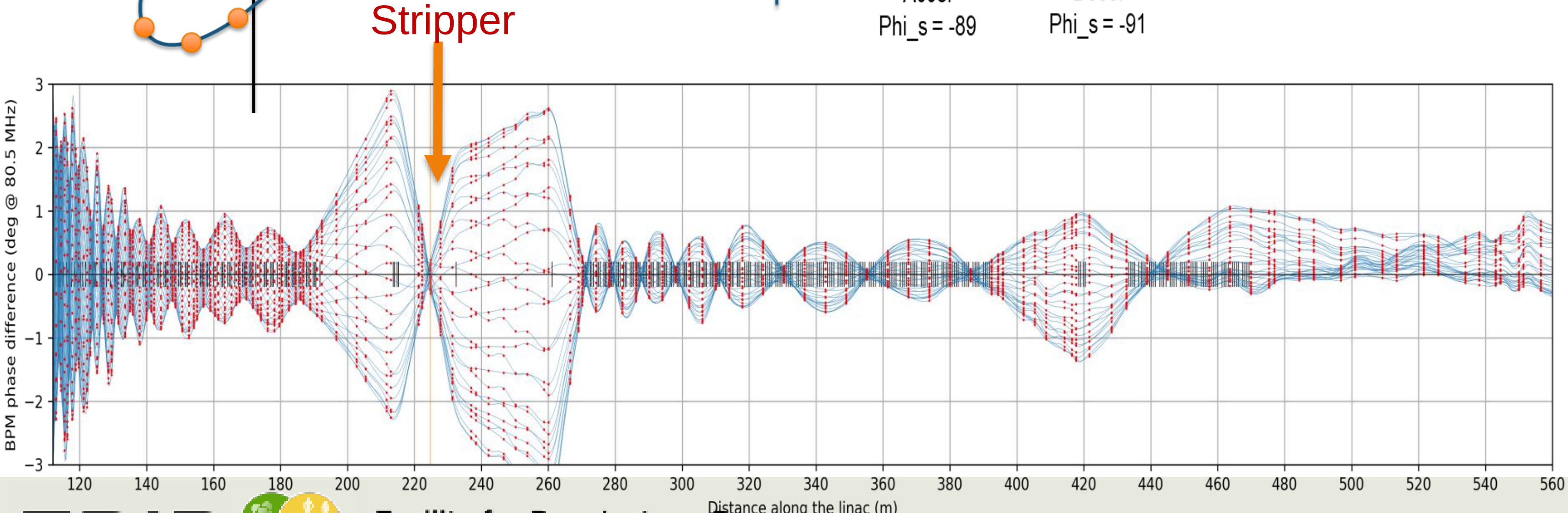


New Tool: Envelope Mapping

- Excite coherent oscillations in the phase space by placing bunch center on Twiss’ ellipse. Collect data from 144 BPMs along the linac.

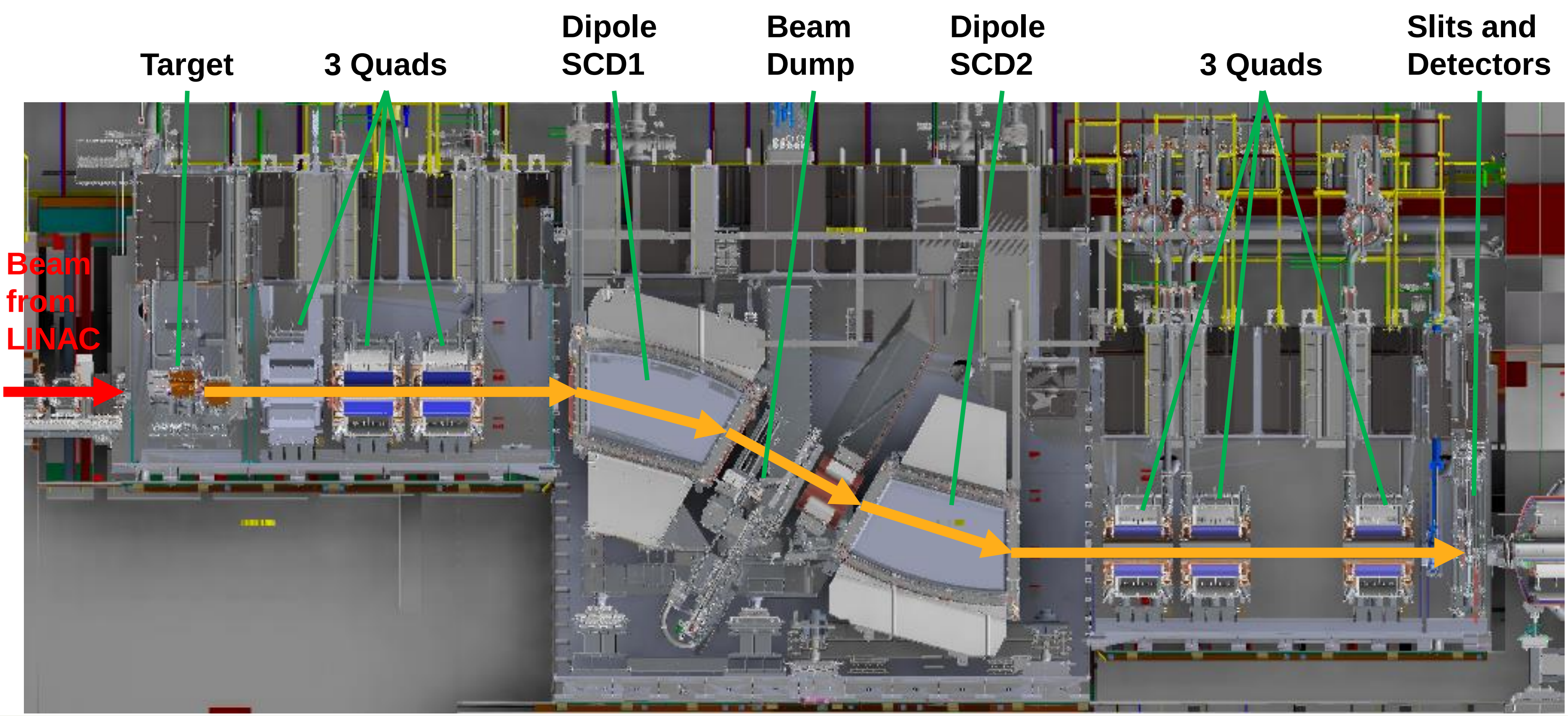






Layout of Target Hall Optics for Separation of Selenium Isotopes

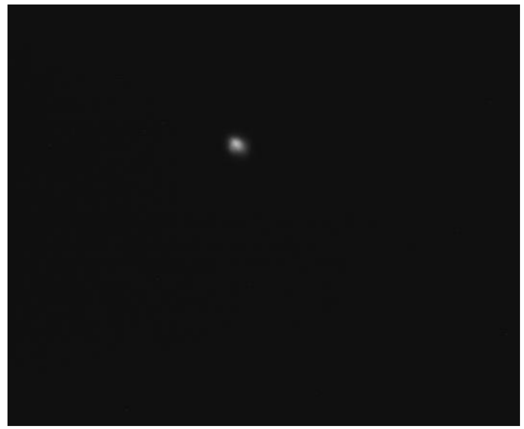
- 3 mm C target and 3.34 mm thick Be target
- The momentum acceptance of separator is dp/p=0.1%.



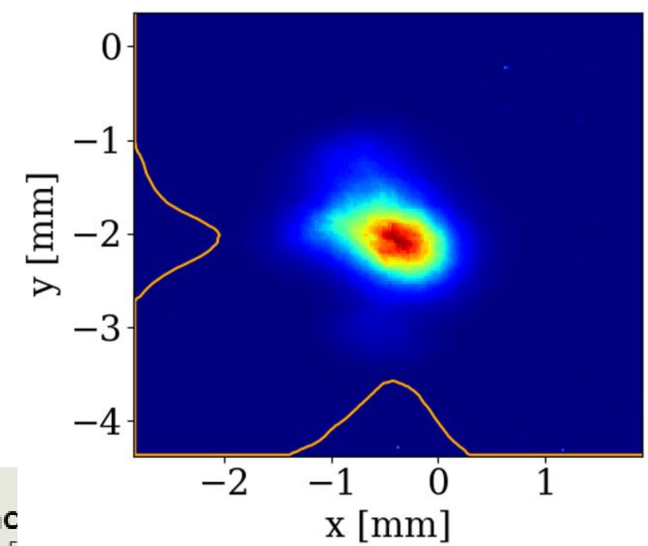
^{86}Kr Beam Images Observed during ARR06

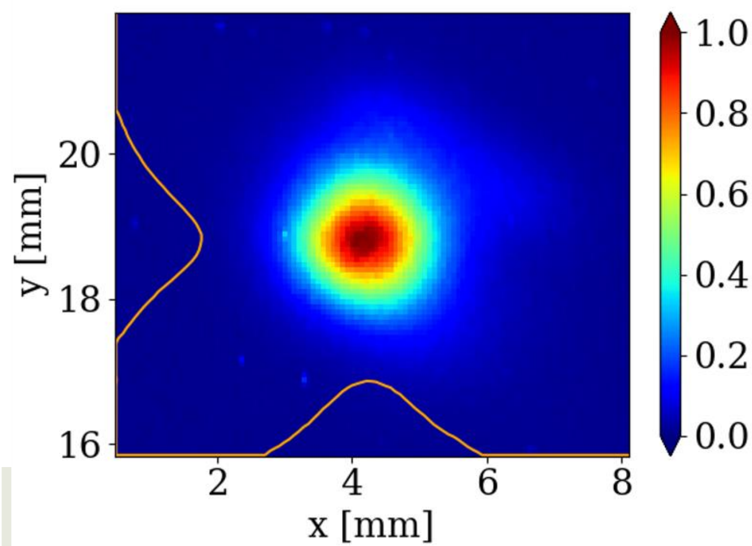
- RMS beam size on the viewer – 0.3 mm
- RMS beam size on the wedge – 0.6 mm
- Consistent with simulations

Target Viewer



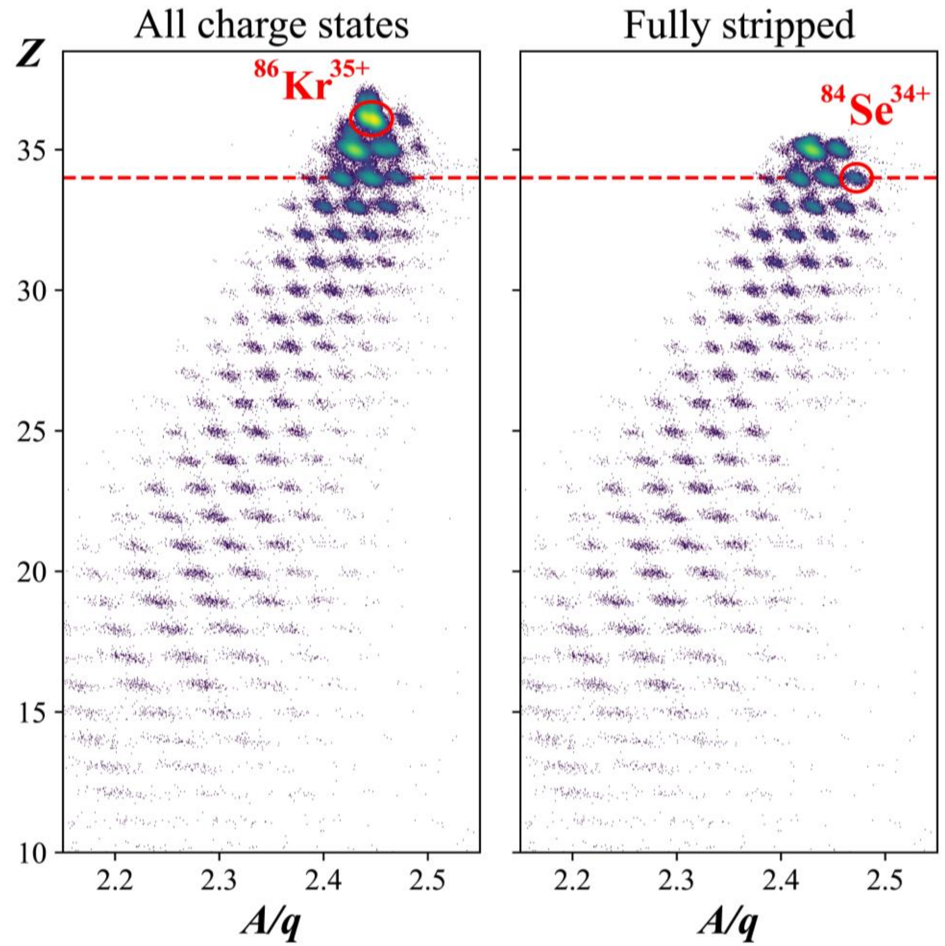
Wedge Viewer





Identification of Selenium Isotopes

- Silicon detectors were calibrated with primary beam of known energy
- Measured data for each single particle
  - Time-of-flight from target to PIN telescope → A/q
  - Energy loss in silicon detector → Z
  - Total kinetic energy → q
- ^{84}Se is unambiguously identified
  - Ion with the highest Z is ^{86}Kr, primary beam
  - $^{84}Se^{34+}$ (q=Z) is identified using all three measured parameters



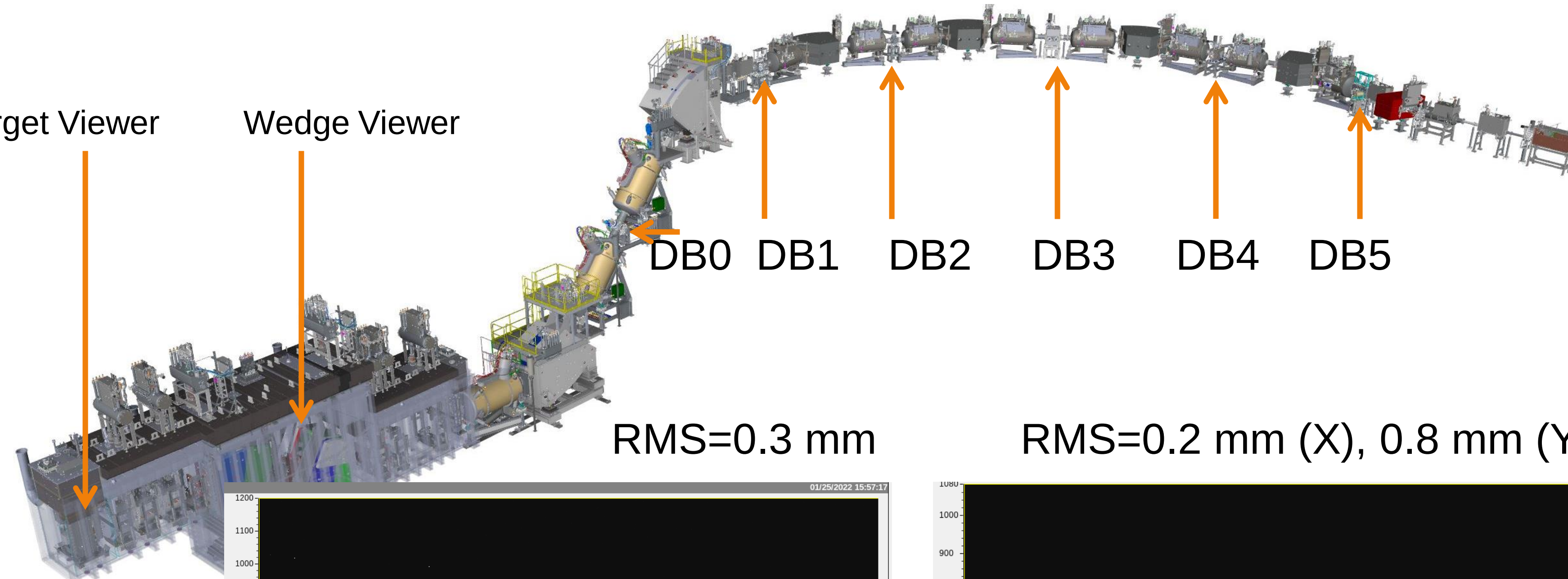
FRIB Installation Progress on Webpage

- https://frib.msu.edu/news/photo-gallery/frib-project-progress-2017.html
- Secondary beamlines →

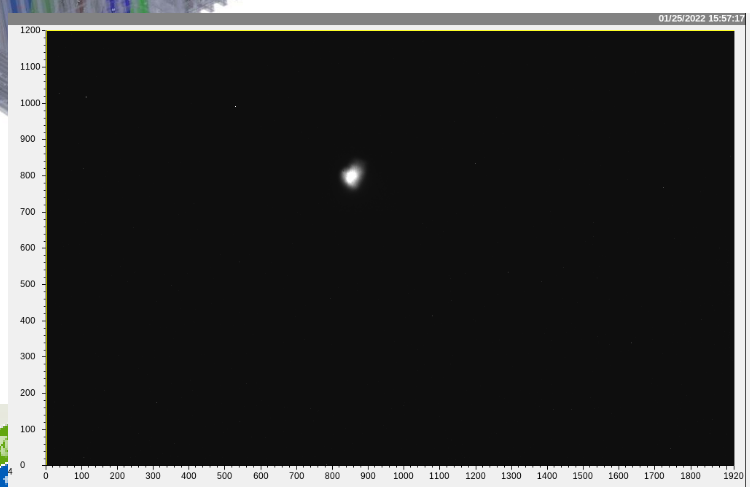
- Installation of 140 T magnet

Beam Transport to ARIS Focal Plane

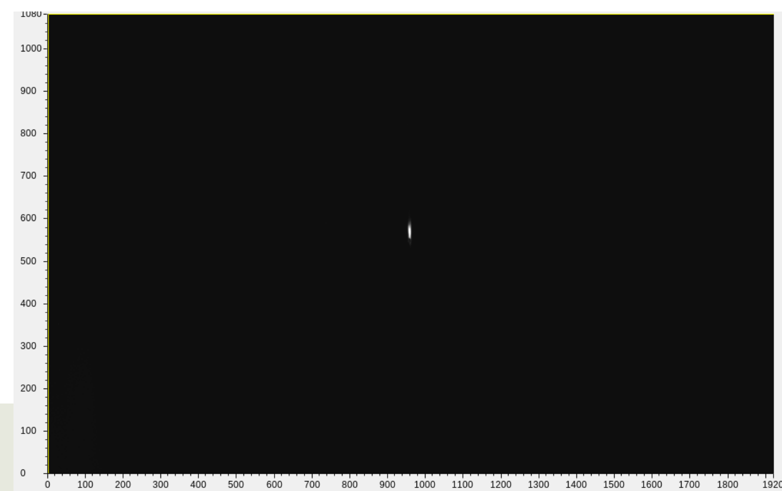
- Magnets were set based on pre-calculated beam optics
  - Effective length of magnets obtained from mapping



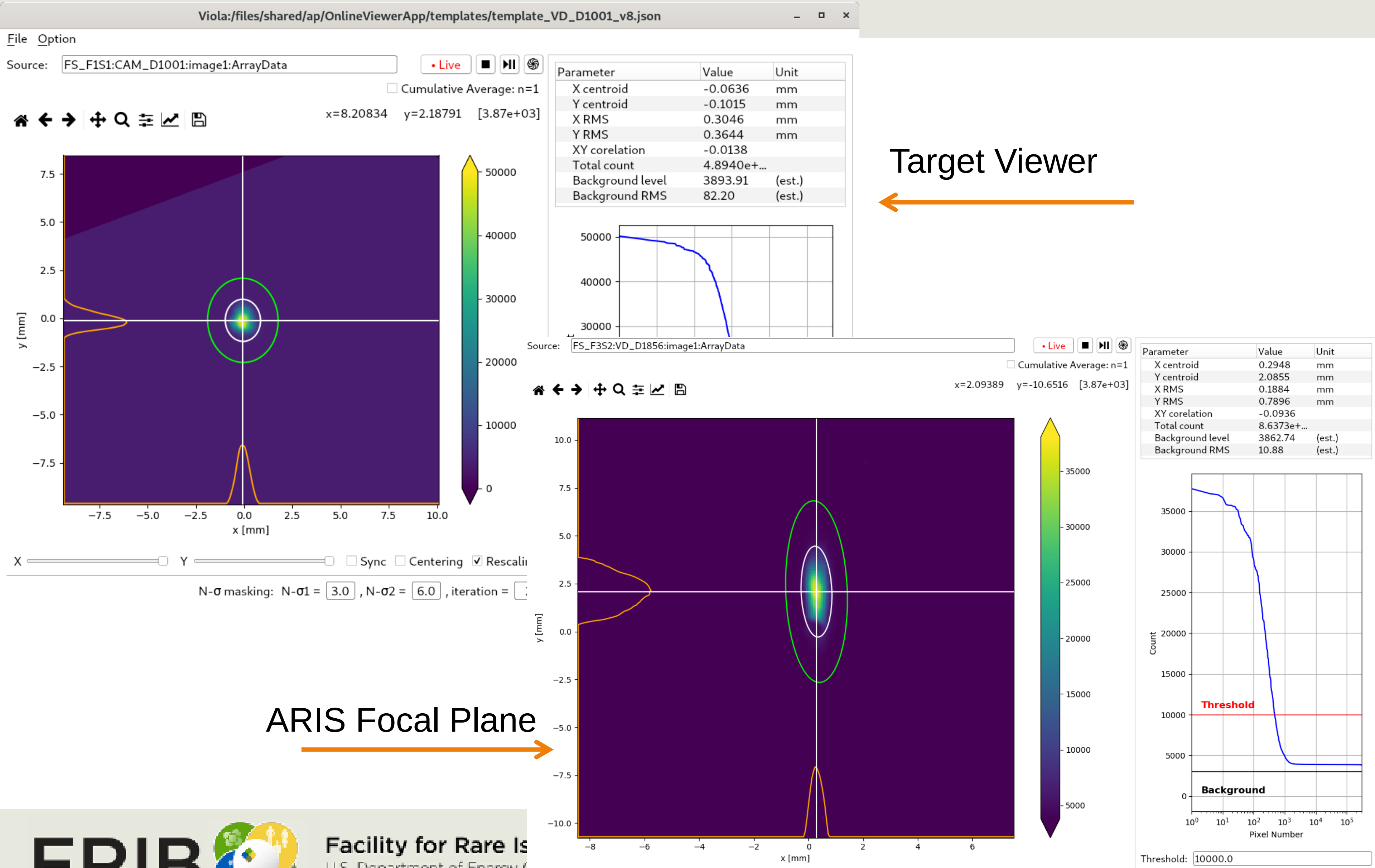
RMS=0.3 mm



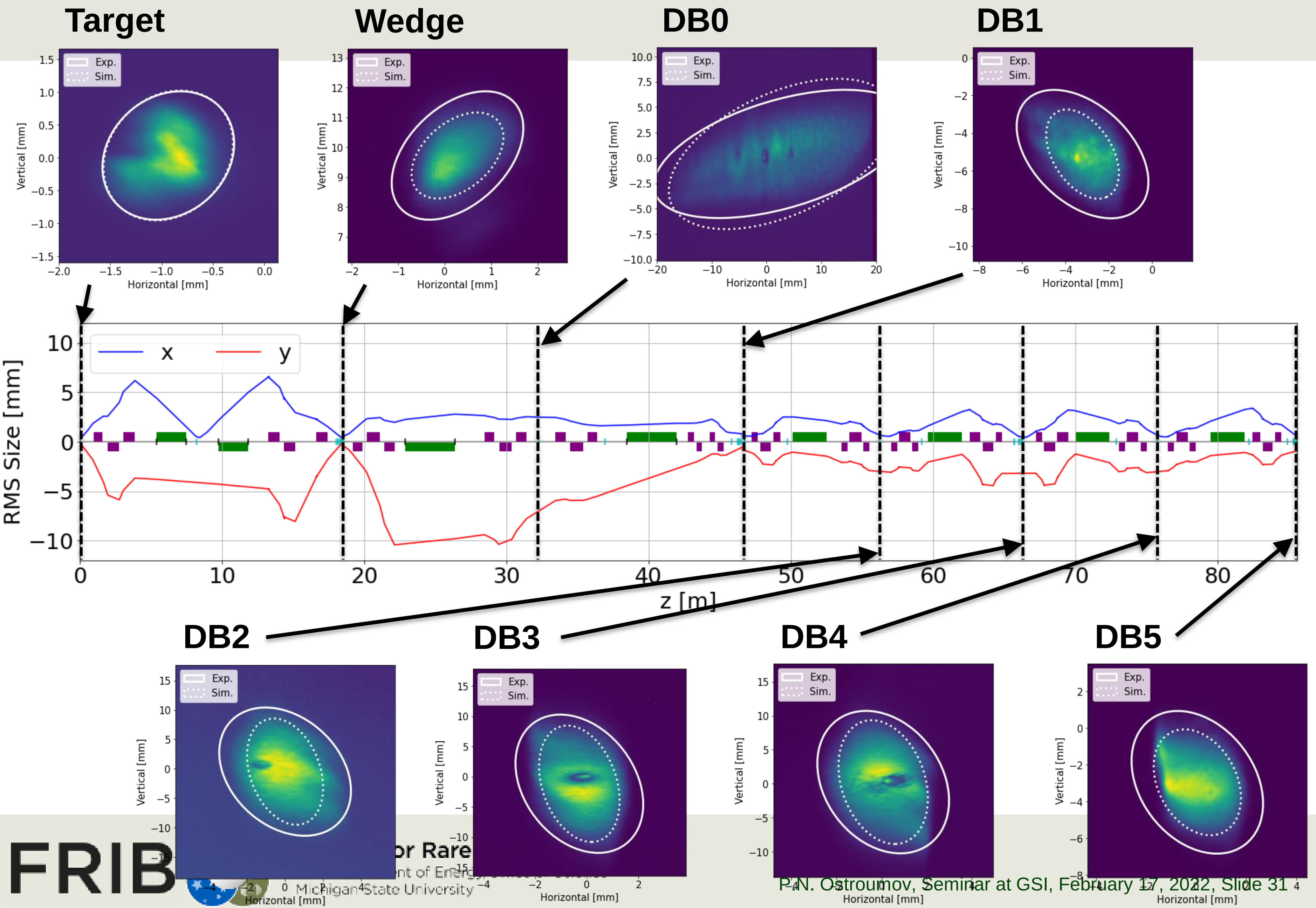
RMS=0.2 mm (X), 0.8 mm (Y)



Beam Distributions on Target and Focal Plane



210 MeV/u $^{36}Ar^{18+}$ Beam Envelope in ARIS

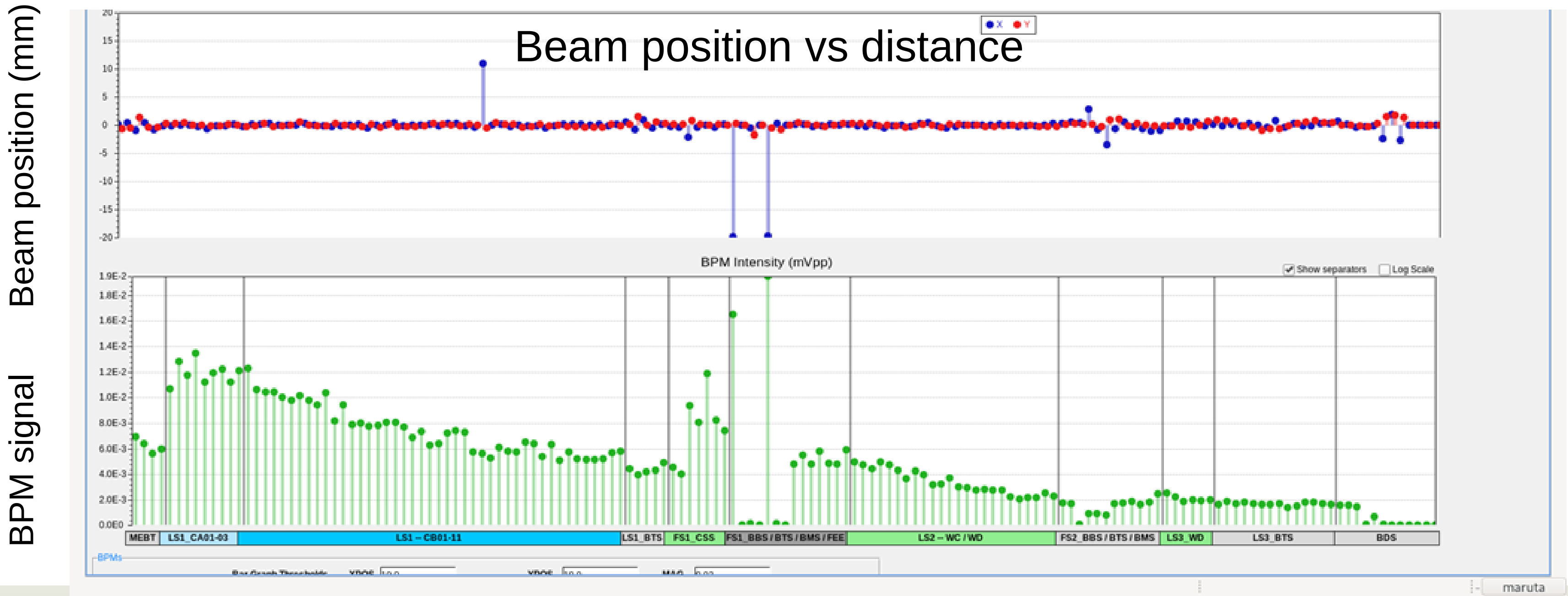


Summary

- Beam commissioning of the FRIB is complete
- Multiple ion species accelerated above 200 MeV/u
- The accelerator 3D models predict the beam dynamics very well
- Many HLAs were developed and being used to set up the accelerator and fragment separator
- The first experiments are scheduled in May 2022
  - PAC1 approved 34 experiments
- 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

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