Beam Commissioning at FRIB

Speaker: Tomofumi Maruta

Facility for Rare Isotope Beams at Michigan State University

ARIES workshop, January 25, 2021

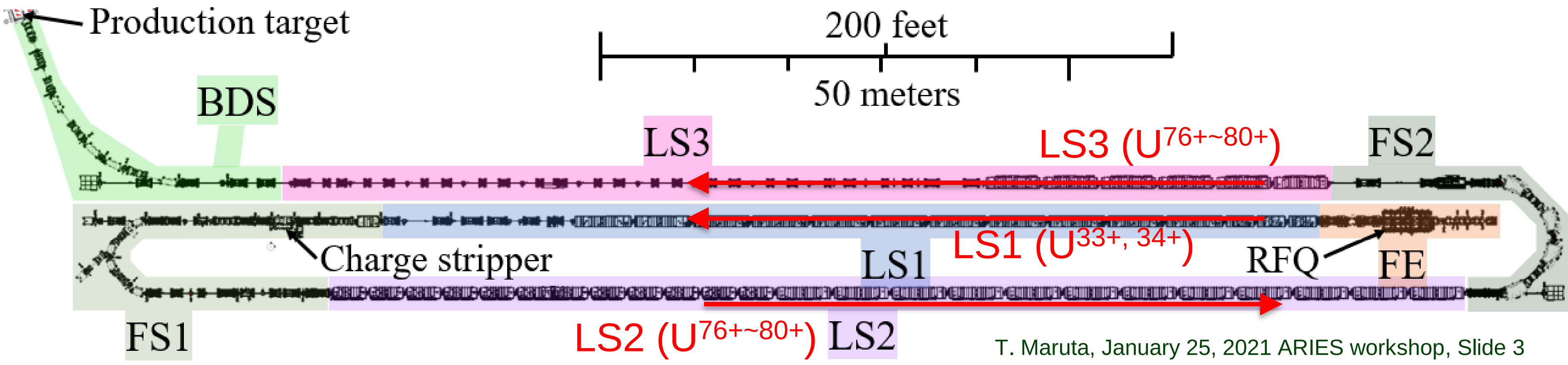
This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Outline of the Talk

- Brief description of FRIB injector linac
- Outline of phased beam commissioning of the linac
- Beam study results from Front-end to the 2nd linac segment
- Summary

Outline of FRIB Injector Linac

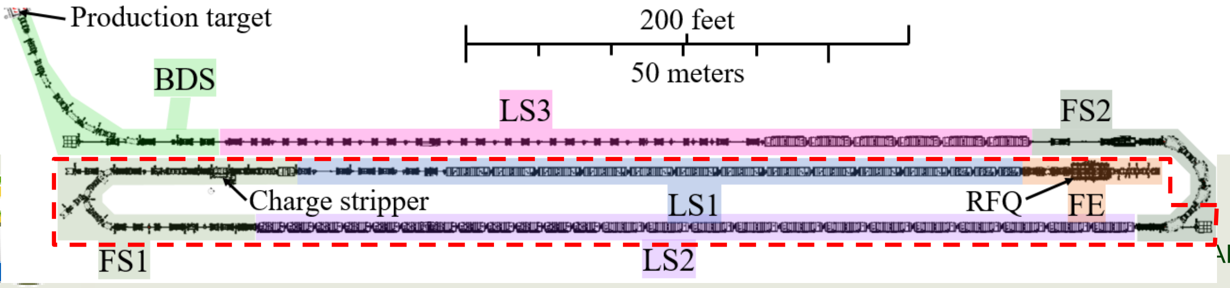
- Accelerate all stable ion species more than 200 MeV/u by > 300 superconducting RF resonators
- Provide beam power of 400 kW for all ions on the production target
- Two folding beam line in the accelerator tunnel
  - Front-end (IS, LEBT, RFQ and MEBT), 3 linac segments (LS1~3), 2 folding segments (FS1, 2) and a beam delivery system (BDS) to the production target
- Flexibility of beam duty (CW, pulsed)
- Simultaneous multi-charge state beam acceleration
  - ^{238}U: 33+, 34+ from ECR ion source to the charge stripper and 76+ ~ 80+ after that
  - FS1 and FS2 bending sections are designed to ensure both achromatic and isochronous conditions



Phased Beam Commissioning is on-going
Phase-4 Commissioning Completed

- For the injector linac, two commissioning performance requirements defined
  - ^{36}Ar beam with energy > 200 MeV/u and beam current > 20 pnA
  - ^{86}Kr beam to produce ^{84}Se by fragmentation
- Six-phased beam commissioning are planned from upstream
  - Beam test started at May 2017
  - Up to now, Phase 4 was successfully completed

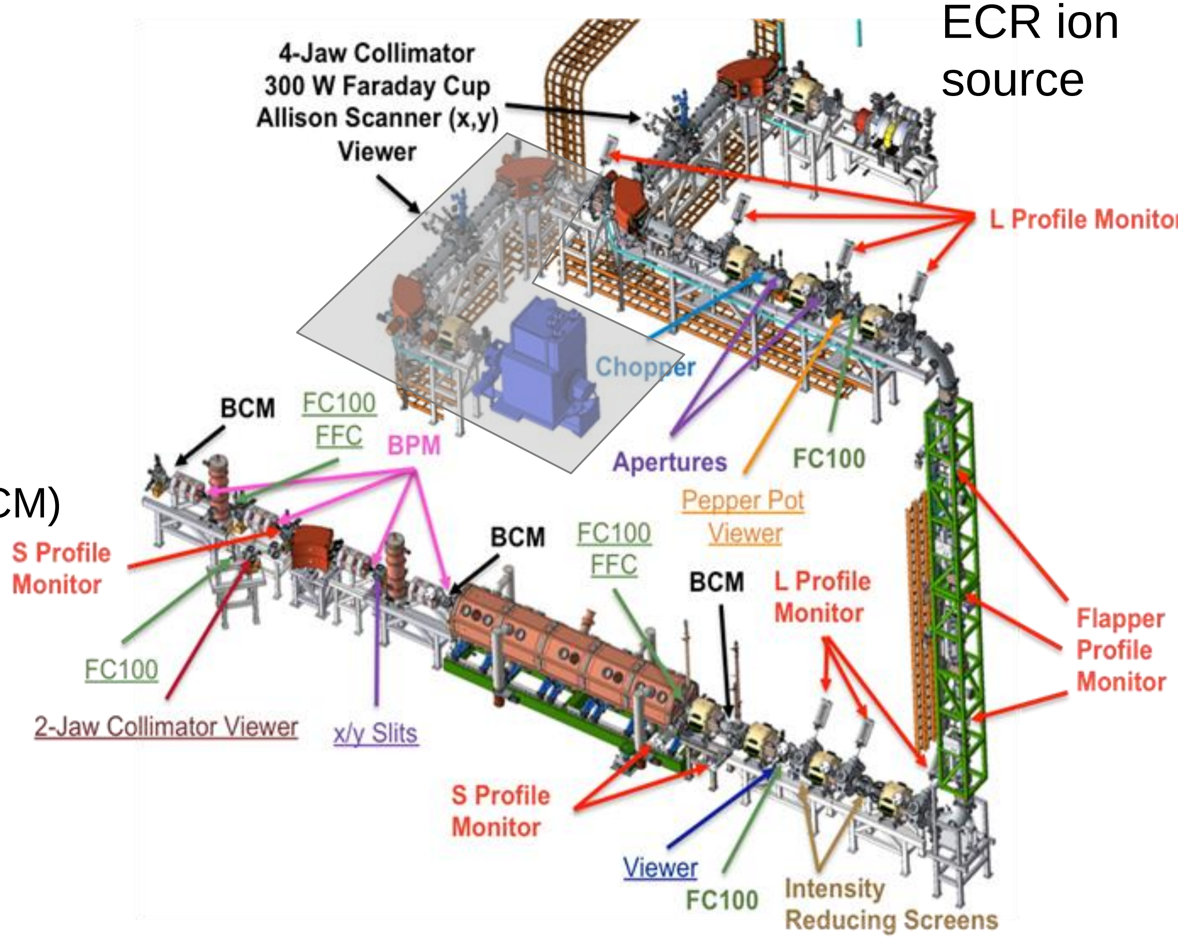
Phase	Area with beam	Energy [MeV/u]	Date	
Phase 1	Front end (Ion source, LEBT, RFQ, MEBT)	0.5	07/2017	✓
Phase 2	Linac Segment (LS) 1 with β = 0.041 cryomodules	2	05/2018	✓
Phase 3	Rest of LS1 and first dipole of Folding Segment (FS) 1	20	02/2019	✓
Phase 4	Rest of FS1, LS2, part of FS2 to straight dump	200	03/2020	✓
Phase 5	Rest of FS2, LS3, Beam Delivery System (BDS) straight section	> 200	04/2021	
Phase 6	Target hall preseparator	> 200	10/2021	



FRIB

Front End Beam Instrumentation

- Set of diagnostics device are available for beam tuning and finding setpoints of optical devices
  - Beam profile and position measurement
    - » Allison emittance scanner
    - » Pepper pot
    - » Image viewers
    - » Wire profile monitors
    - » Beam position monitors (BPM)
  - Beam current measurement
    - » Faraday cups (FC)
    - » Beam current transformers (BCM)
  - Beam interceptive device
    - » 4-Jaw Charge selection slits
    - » Apertures
  - Intensity control
    - » Electrostatic chopper
    - » Intensity attenuators



LEBT Beam Profile Measurements

- before the phase-1 beam commissioning, Front-end optics was developed for ^{40}Ar
  - Analysis scripts for Allison scanner, PM and image viewer were developed
  - FLAME (matrix), TRACK (PIC) and IMPACT (PIC) simulation code were prepared
- Snapshots of image viewers and a TRACK simulation are agreed well

Reconstructed RMS beam envelope by FLAME from 8 PMs and 1 Allison scanner measurements

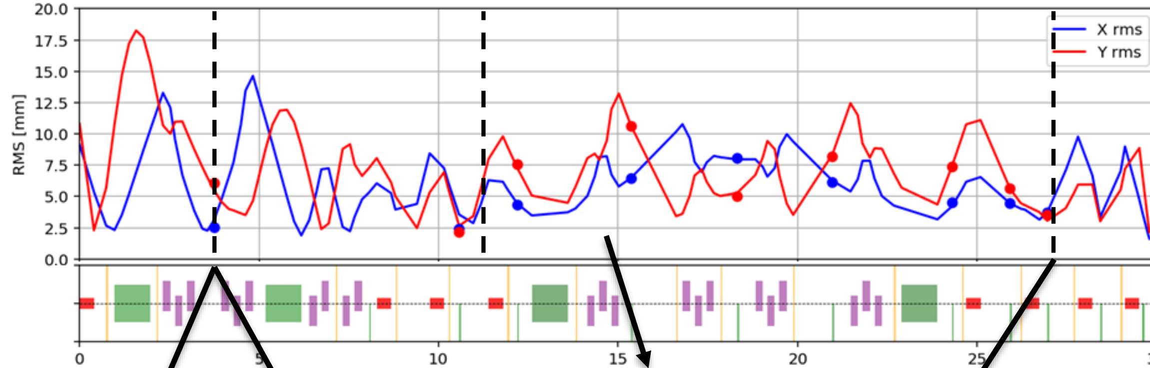
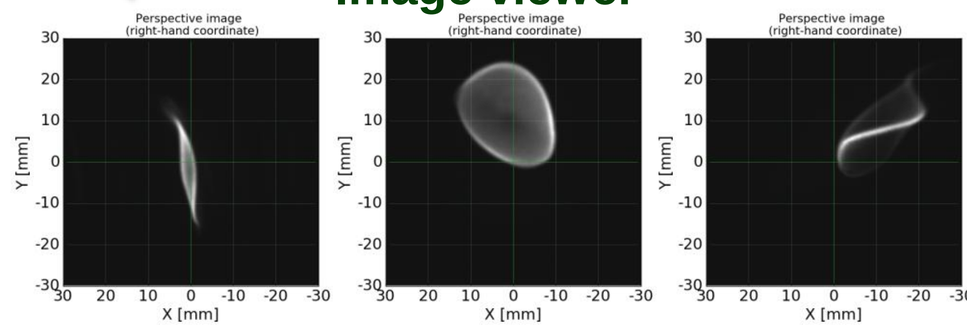


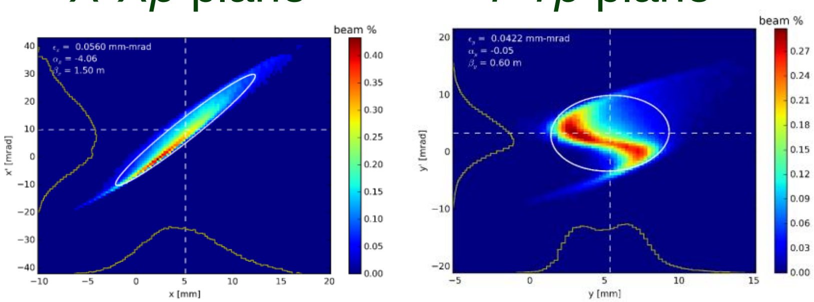
Image viewer



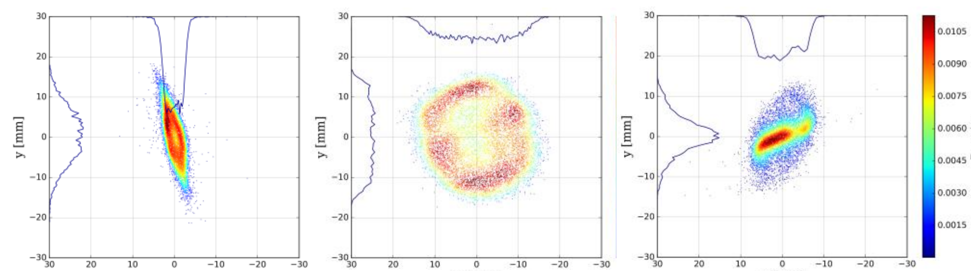
Allison scanner

X-Xp plane

Y-Yp plane

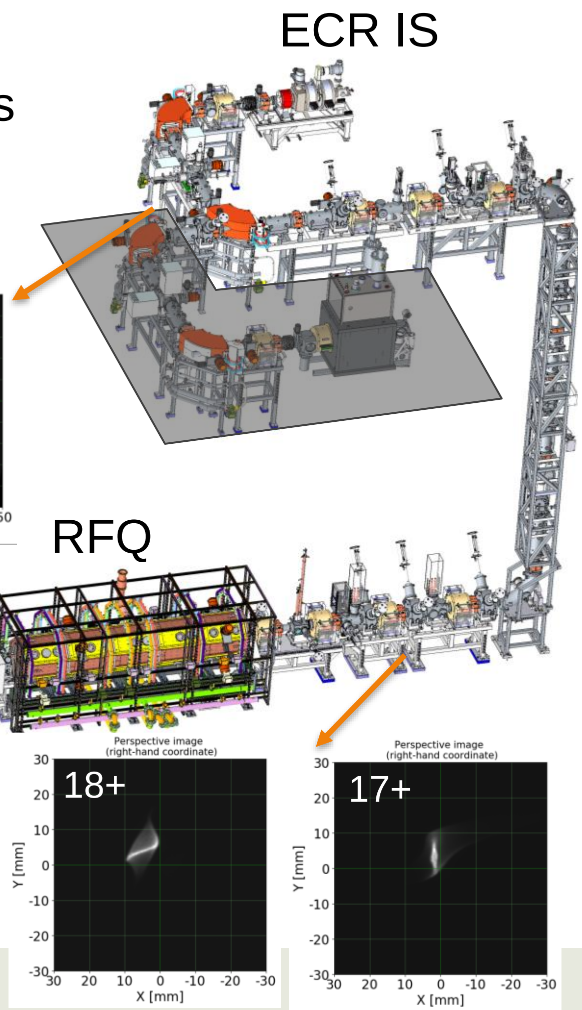


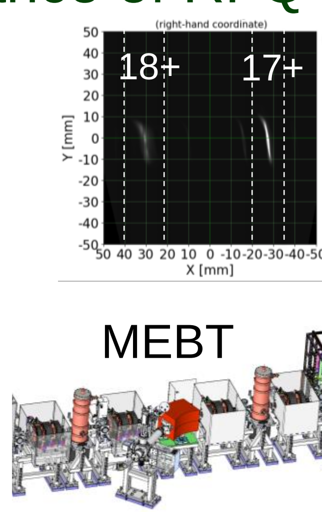
TRACK simulation



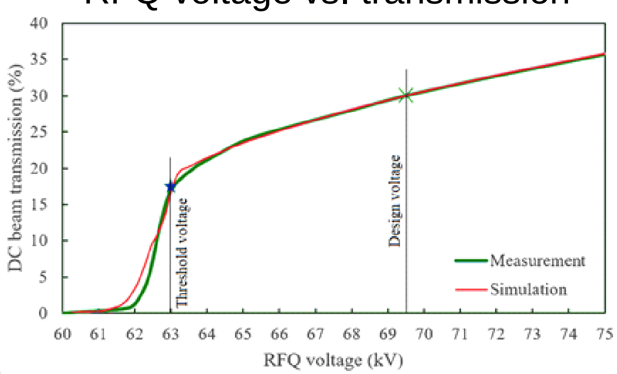
Front End Beam Commissioning (Phase 1) in July, 2017

- ^{40}Ar and ^{86}Kr were successfully accelerated to 0.5 MeV/u by RFQ
  - Beam energy was confirmed by a dipole magnet in MEBT
  - RFQ beam transmission is 85% as design
    - » Correlation of DC beam transmission and RFQ voltage is consistent with a simulation
- $^{86}Kr^{17+,18+}$ are transported to the entrance of RFQ without any optics change
  - $\Delta q/q$ = ~ 6%, almost twice of ^{238}U
  - ~100% beam transmission to the RFQ entrance





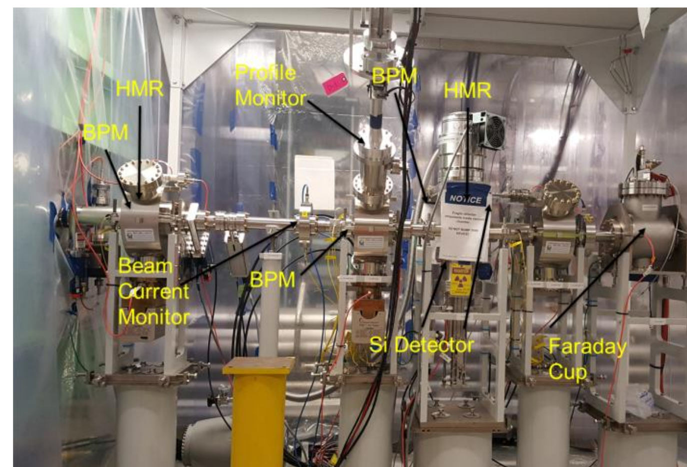
RFQ voltage vs. transmission



Beam Commissioning of the First 3 Cryomodules in Phase 2 (May, 2018)

- First beam acceleration by superconducting RF resonators
  - Accelerate Argon beam up to 2.0 MeV/u by twelve β = 0.041 Quarter Wave Resonators (QWR) in three cryomodules
    - » Design energy: 1.5 MeV/u

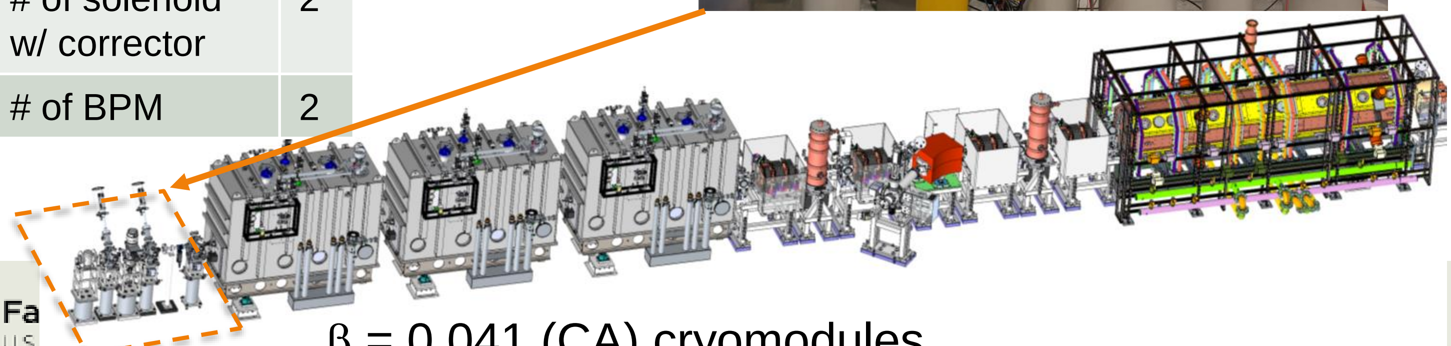
- Temporary diagnostics station (D-station) was constructed after the cryomodules
  - Absolute beam energy measurement by a SiD
  - Beam profile measurements in both transverse and longitudinal phase space
  - Beam diagnostics test



Resonator and cryomodule parameters

Resonator	
β_{OPT}	0.041
type	QWR
f [MHz]	80.5
V_{acc} [MV]	0.8
r_{apr} [mm]	36

CA Cryomodule	
# of cavity	4
# of solenoid w/ corrector	2
# of BPM	2

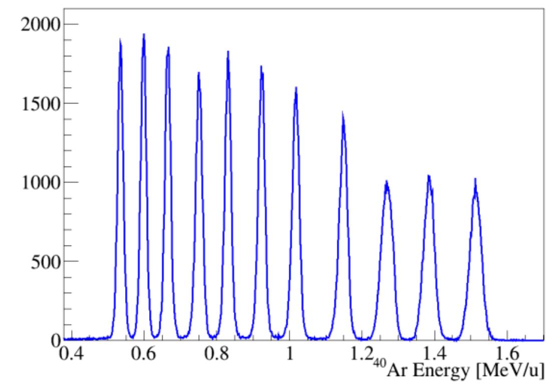


β = 0.041 (CA) cryomodules

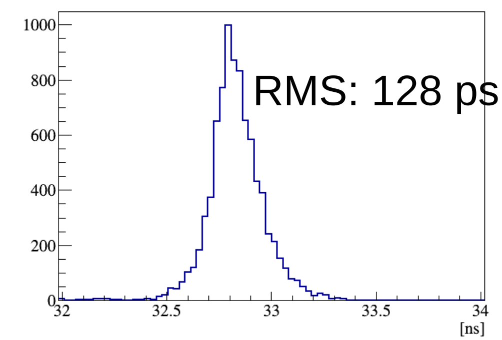
Highlights of Phase-2 Beam Commissioning

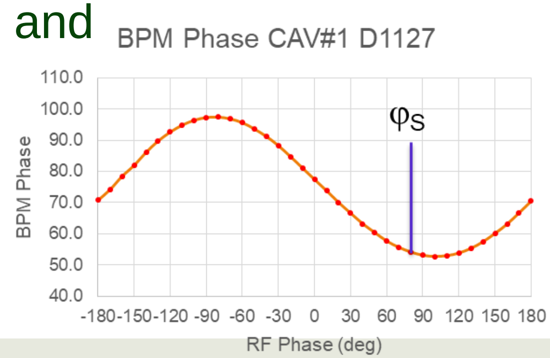
- Accelerate both 40Ar and 86Kr to 2.0 MeV/u by 11 SRF cavities
  - The absolute energy and longitudinal bunch size were measured by SiD
- Phase scan application developed by python script is worked well
  - Energy is calculated from time-of-flight of two BPMs
  - Only 0.2 euA is necessarily to measure bunch arrival timing w.r.t the reference RF
  - Scan at 20% design amplitude to determine driven phase and then increase its amplitude to get design energy
- Transverse and longitudinal emittance were measured in D-station
- Machine protection system is tested and activated to run high power beam

Beam energy by SiD after finishing each cavity's tuning



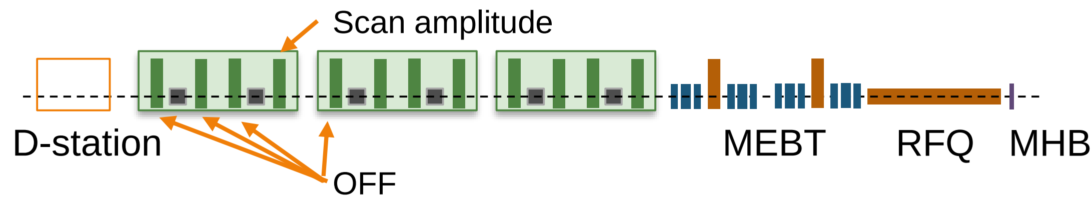
Longitudinal bunch size



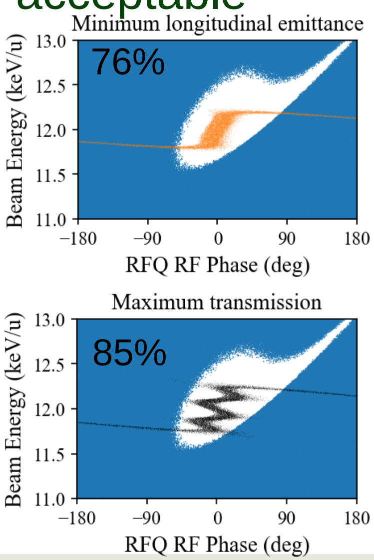


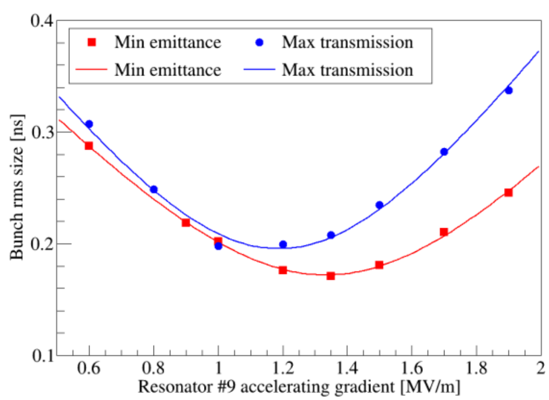
Longitudinal RMS Emittance Measured with Two MHB Settings

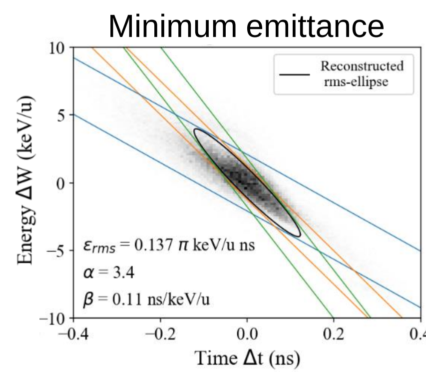
- Multi-Harmonic Buncher (MHB) is to provide bunched beam to RFQ
  - Three harmonics of 40.25, 80.5 and 120.75 MHz
- Measured longitudinal emittance with two MHB settings
  - Measure longitudinal bunch length by the SiD with varying the amplitude of 9th resonator
  - Minimum longitudinal emittance
  - Maximum beam transmission

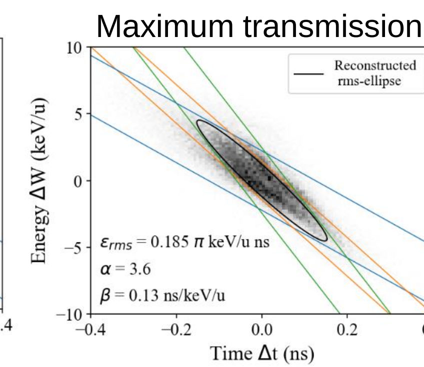


- However the emittance with max. transmission is grater, it is still acceptable









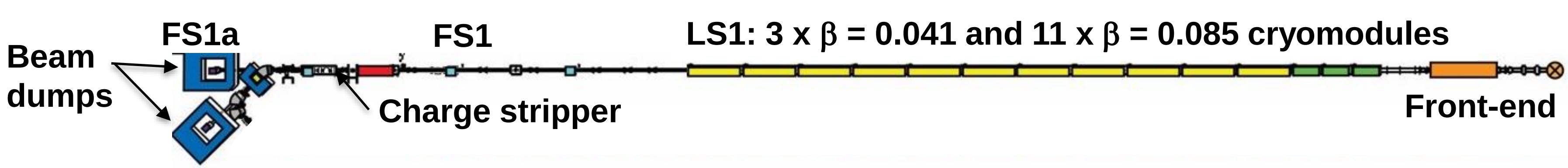
[πkeV/u nsec]	Meas.	Sim.
Min. emit.	0.14	0.12
Max. trans.	0.19	0.14

Beam Commissioning of LS1 in Phase 3 (Feb. 2019)

- The functions were successfully verified
  - Four ion species of ^{40}Ar, ^{86}Kr, ^{20}Ne and ^{129}Xe accelerated to 20 MeV/u
  - Demonstrated charge stripping with the carbon foil stripper
    - » While 1st year user operation is planned to use rotating carbon stripper, an liquid lithium stripper will be installed for high power operation
- Further beam studies were also completed successfully
  - Transverse and longitudinal emittance after LS1 were measured
    - » No emittance growth observed for transverse
  - ~300 W beam transported to FS1b without any beam loss
    - » CW operation, and high peak current with low duty
  - Two charge state ^{86}Kr acceleration with identical MEBT to FS1 setting
  - Fault scenario study
    - » One cavity and one cryomodule fault

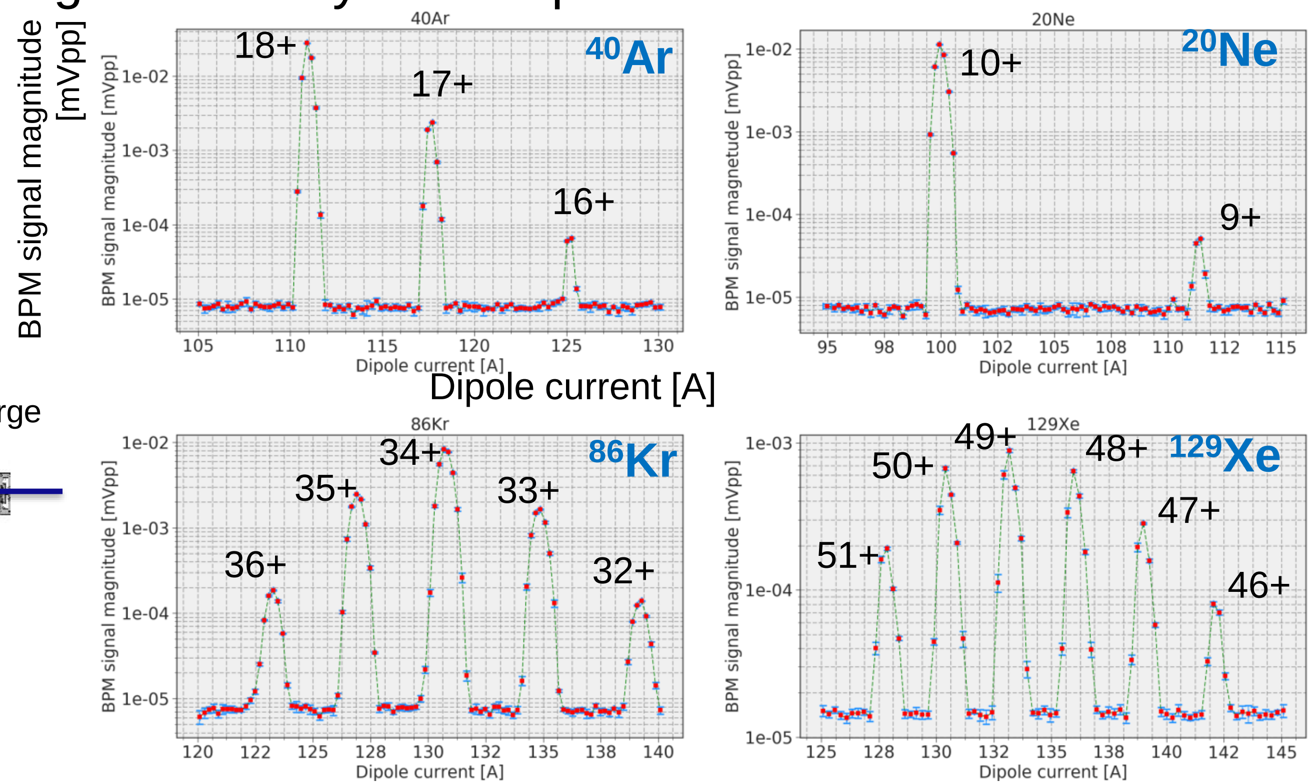
Parameter of cryomodules

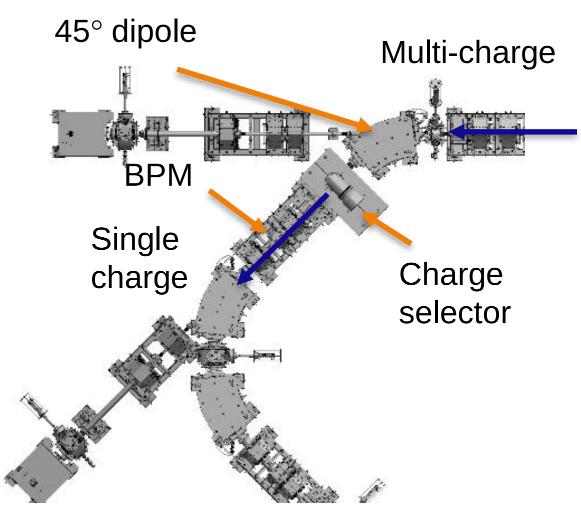
Cryo type	CA	CB
Cavity		
β_{OPT}	0.041	0.085
type	QWR	
f [MHz]	80.5	
V_{acc} [MV]	0.8	1.8
r_{apr} [mm]	36	36
Cryomodule		
# of cavity	4	8
# of solenoid w/ corrector	2	3
# of BPM	2	3



Charge State Distributions after the Stripper Measured for Four Ion Beam Species

- 0.8 mg/cm^2 carbon foil was inserted on the beamline
- Scan 45° dipole current with monitoring magnitude of the Beam Position Monitor (BPM) signal after the charge selector slits adjusted for 4 mm horizontal aperture
  - Very low noise and high sensitivity of 0.1 eμA level beam current
- Charge states are isolated well to be selected by the charge selector



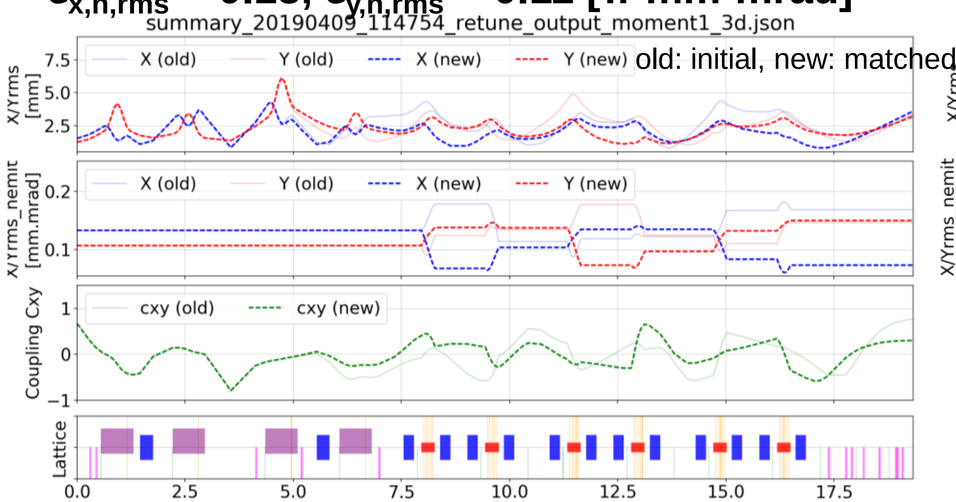


Transverse Beam Parameters are Consistent with Design Parameters

- Transverse envelope were matched to downstream optics
  - Estimate beam envelope based on profile monitor (PM) measurements
  - Optimize four quadrupole fields for an envelope matching
    - » LS1 injection matching by MEBT last four quadrupoles
    - » FS1 injection matching by LS1 last four quadrupoles
- No significant emittance growth during LS1

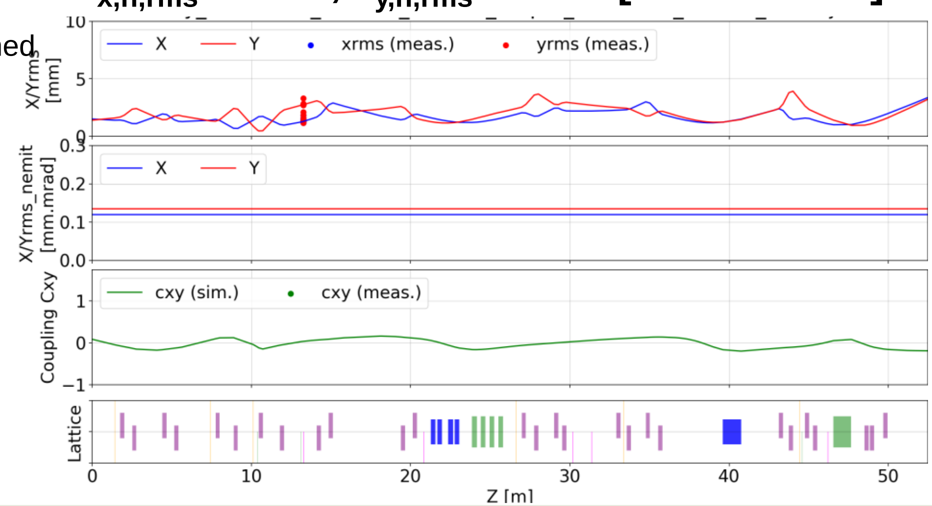
MEBT matching

$\varepsilon_{x,n,rms}$ = 0.13, $\varepsilon_{y,n,rms}$ = 0.11 [π mm-mrad]



FS1 reconstructed envelope

$\varepsilon_{x,n,rms}$ = 0.12, $\varepsilon_{y,n,rms}$ = 0.13 [π mm-mrad]

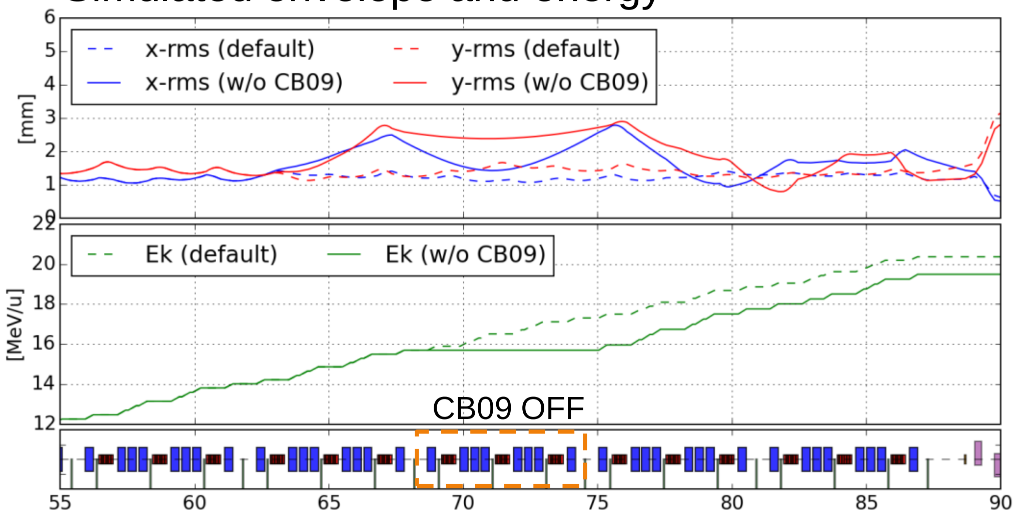


Fault Study: One Cryomodule Off

Beam is Accelerated up to 19.5 MeV/u w/o Significant Losses

- All resonators and solenoids in CB09 were off
- Tune CB08 and CB10 solenoids to compensate missing solenoids
- 2π phase scan tuning to the cavities in CB10 and CB11
  - 14% higher voltage and -15° synchronous phase to recover energy
  - Additional tuning will be done in LS2 to completely recover energy
- 100% BCM transmission was achieved to FS1, however beam fraction of 5×10^{-4} was detected with the HMR after CB09

Simulated envelope and energy



^{86}Kr Two Charge States Acceleration

Capability of LS1 Dual Charge States Acceleration Demonstrated

- Charge difference is twice of Uranium beam
  - Beam is more mismatched than design

$^{86}Kr^{17+,18+}$ $\quad$ $^{238}U^{33+,34+}$

$$\frac{\Delta q}{q} = 5.7\% \quad \Longleftrightarrow \quad \frac{\Delta q}{q} = 3.0\%$$

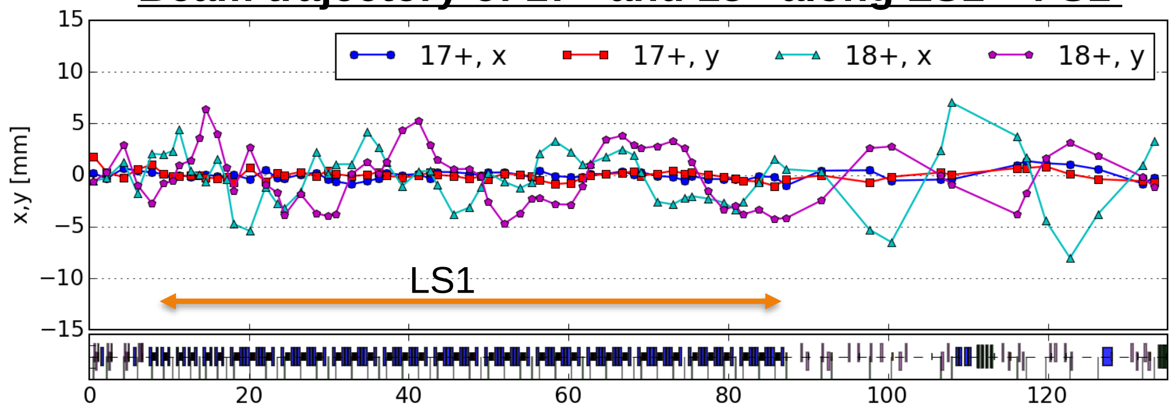
- Everything is tuned for $^{86}Kr^{17+}$
  - Beam trajectory aligned within $\pm$1 mm
  - Transverse matching was conducted at the FS1 entrance
- ECR IS and LEBT are tuned to $^{86}Kr^{18+}$ because a velocity equalizer at the RFQ entrance is absent at present
  - Extraction voltage is set for 18+ to be 12 keV/u
  - Scale LEBT optical elements by 17/18

Energy after LS1

[MeV/u]	17+	18+
LS1 end	20.30	20.26

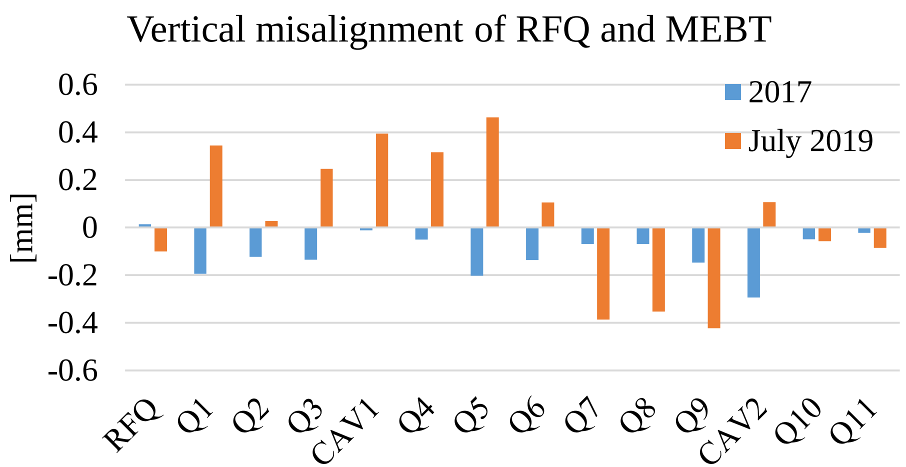
- While transmission is 100%, trajectory is displaced up to 7 mm

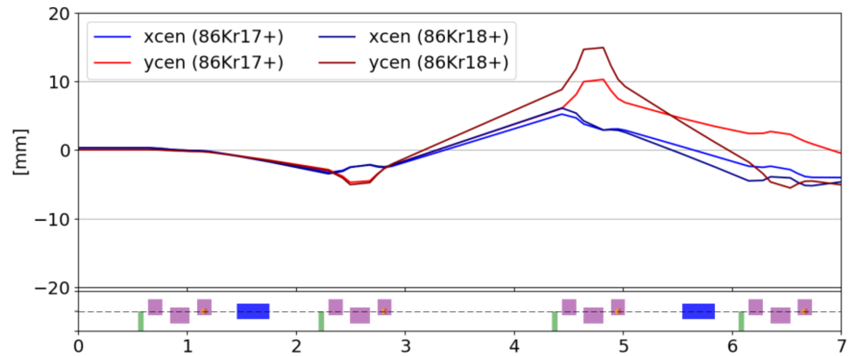
Beam trajectory of 17+ and 18+ along LS1 – FS1



Misalignment of Front-end Elements Cause the Trajectory Displacement

- One of the main reason of trajectory displacement is misalignment of front-end optical elements
- All elements were aligned within requirement of 0.2 mm when installed in 2017
- However, the floor was deformed by cryomodule weight installed later
  - Optical elements were misaligned up to +/-0.5 mm
- Simulation shows the



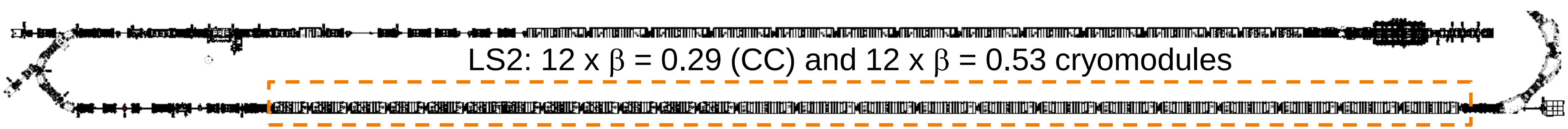


Δ(17-18)	dx [mm]	dxp [mrad]	dy [mm]	dyp [mrad]
MEBT end	-0.7	2.2	-4.7	3.1

Beam Commissioning of LS2 (March and October, 2020)

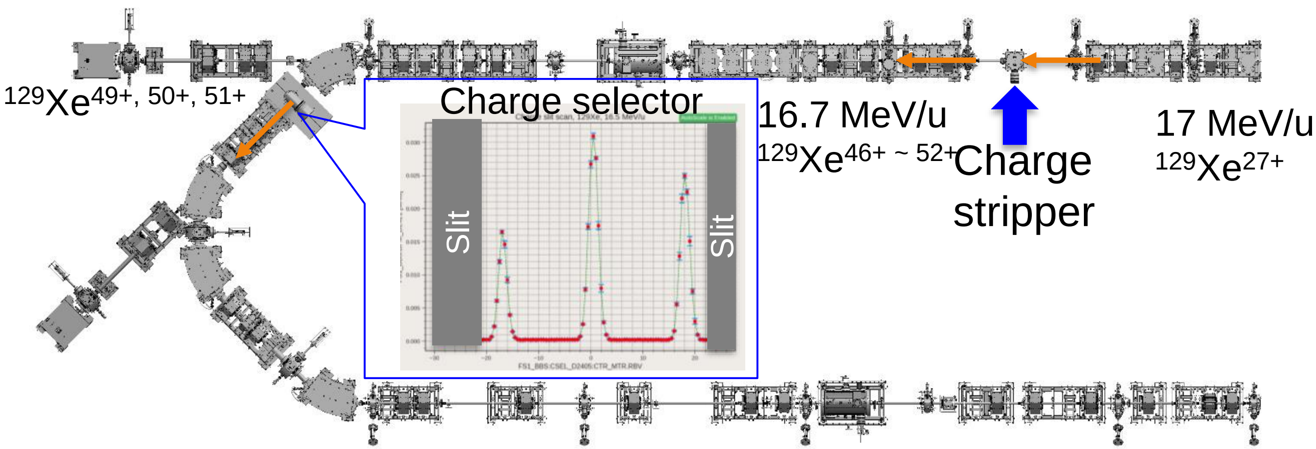
- The functions were successfully verified
  - ^{36}Ar was accelerated to 204 MeV/u in LS2, and ^{129}Xe and ^{86}Kr were > 180 MeV/u
    - » ^{129}Xe setting was scaled to ^{86}Kr and LS1 downstream to LS2 resonator were tuned to compensate energy loss difference at the charge stripper
- Multi-charge state accelerations are demonstrated
  - Achromatic and isochronous condition in FS1 bending section
  - Three charge states of ^{129}Xe
  - Two charge state of ^{86}Kr
  - No beam loss was observed except for near the stripper and beam dump

Cryo type	CC	CD
Cavity		
β_{OPT}	0.29	0.53
type	HWR	
f [MHz]	322	
V_{acc} [MV]	2.1	3.7
r_{apr} [mm]	40	40
Cryomodule		
# of cavity	6	8
# of solenoid w/ corrector	1	1
# of BPM	0	0

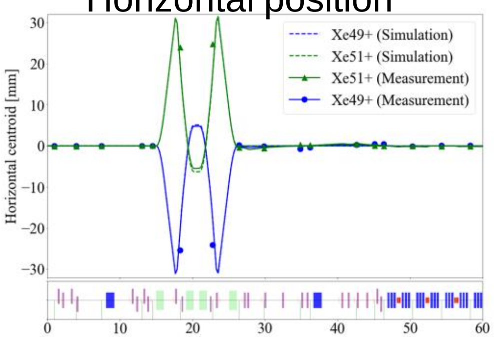


Three Charge State ^{129}Xe Acceleration in LS2

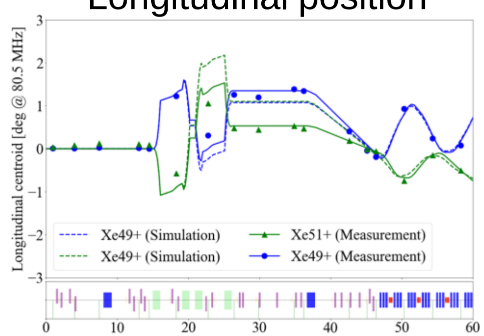
- Three charge states of $^{129}Xe^{49+,50+,51+}$ are simultaneously accelerated by LS2
- Measured transverse and longitudinal beam positions are close to design
- Beam ellipses after LS2 are overlapped so effective emittance is not large and sufficient margin to downstream acceptance



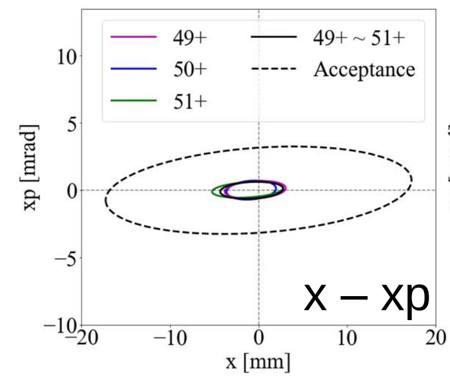
Horizontal position

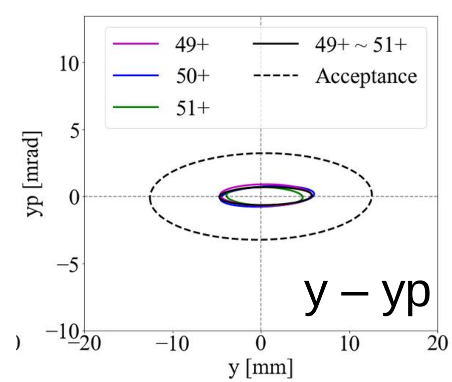


Longitudinal position



5 times RMS ellipse vs. acceptance after LS2



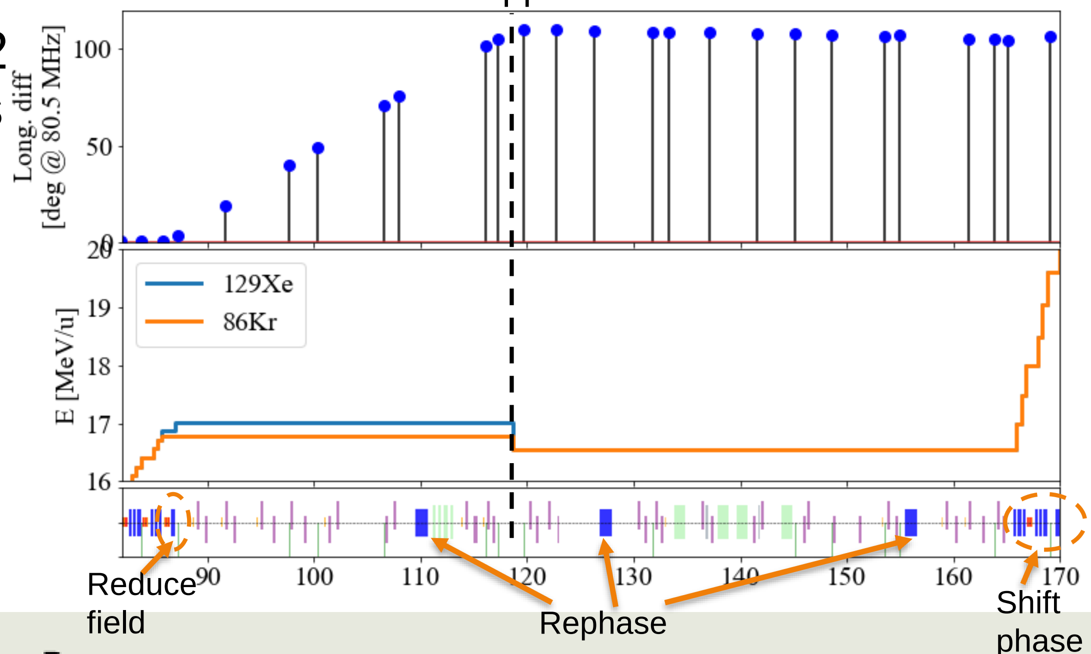


Test of Ion Species Change

- In the user operation, it can be required to change the ion species in short time, so need to minimize tuning procedure
- Test the procedure to switch ^{129}Xe to ^{86}Kr
  - Scale all optical elements and resonators by charge-to-mass ratio
  - Reduce the field of last two resonators in LS1 to get identical energy after the stripper
  - Rephase bunchers in FS1
  - Rephase first resonator in LS2 and shift other LS2 resonators in same amount
- Energy after LS2 is almost identical to ^{129}Xe

Energy after LS2

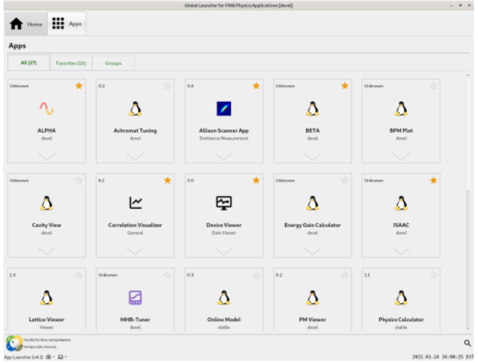
[MeV/u]	^{129}Xe	^{86}Kr
	181.09	181.13



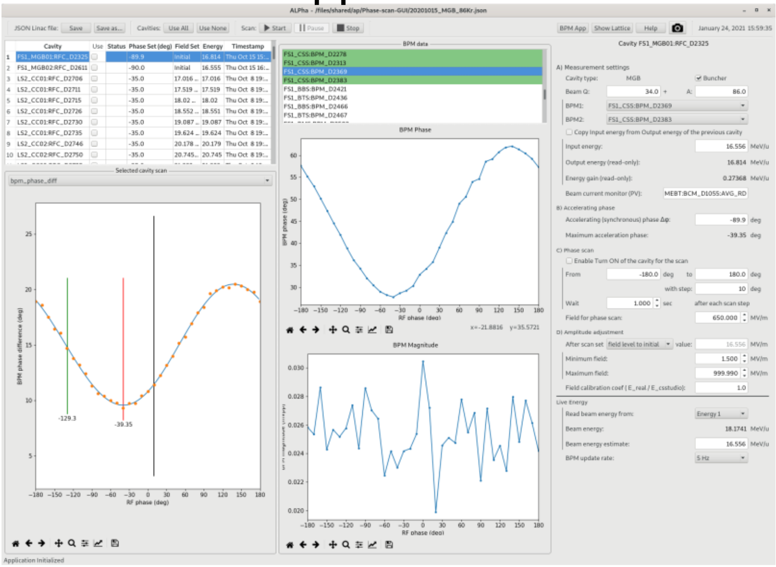
Developments of High Level Applications (HLA)

- High level applications have been developed for beam study
  - All applications are registered to the HLA launcher
    - » So far 37 applications are registered
    - » Operator are available for limited applications
  - Python +Qt platform
    - » Available on any operation system

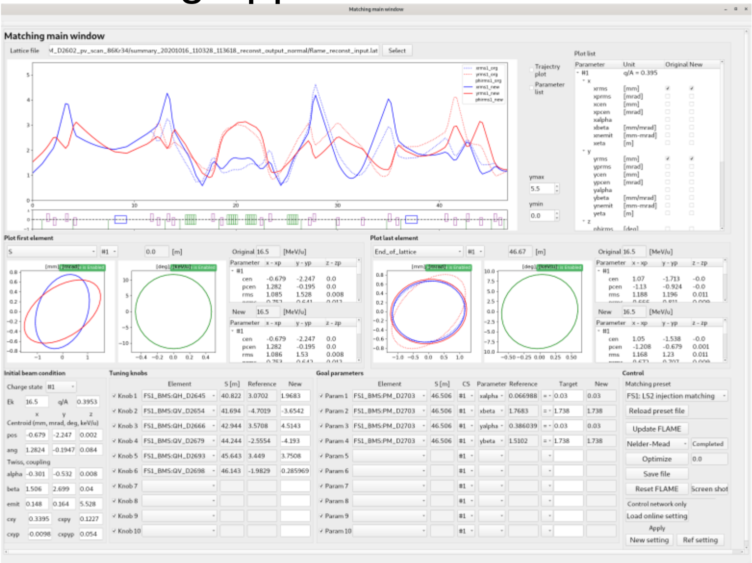
HLA Launcher



Phase scan application



Matching application



Summary

- Up to now, phase-4 beam commissioning of the FRIB injection linac was successfully completed to meet Key Performance Parameter
  - Beam energy was already reached to the requirement for key performance parameter
    - » ^{36}Ar: 204 MeV/u, ^{86}Kr and ^{129}Xe > 180 MeV/u
- Further studies have been conducted
  - Transverse and longitudinal emittance were measured in several locations
  - Proved the multi-charge state simultaneous acceleration and transportation in LEBT, LS1 to LS2
- For user operation, we conducted several beam studies to improve beam availability and beam power
  - Recovery study of one resonator or cryomodule fault
  - Charge state distribution and energy loss at the carbon charge stripper
    - » Li stripper will be installed for high power operation
  - Switching ion source species

Acknowledgments

- I like to thank my colleagues for significant contribution to this work
- Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University.