



Status of Beam Commissioning in FRIB

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Outline of the Talk

- Introduction
- Beam commissioning results in LS1 to FS1
 - Beam acceleration to 20.3 MeV/u
 - Charge stripping by carbon stripper
 - Beam envelope reconstruction and transverse emittance measurements
 - Longitudinal emittance measurement
 - High power test
 - ^{86}Kr multi-charge state acceleration
- Summary

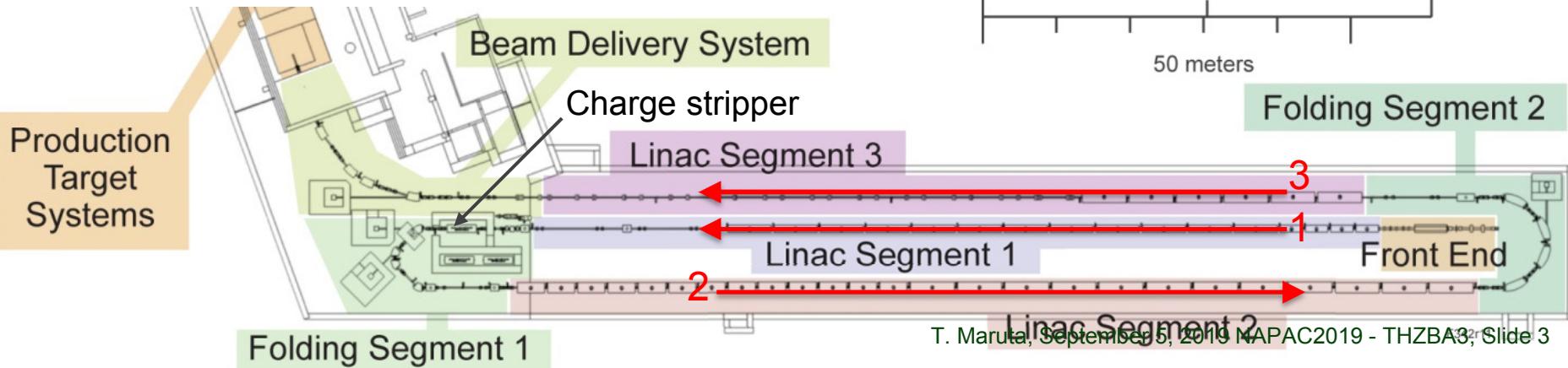
Most of topics are already described in the following papers

- Phys. Rev. Accel. Beams **22**, 040101 (2019)
- Phys. Rev. Accel. Beams **22**, 080101 (2019)



Outline of FRIB Accelerator

- Accelerate all stable ion species more than 200 MeV/u by superconducting (SC) RF resonators
 - 316 SC RF resonators in 46 cryomodules
- Provide beam power of 400 kW for all ion species on the production target
- Multi-charge state beam acceleration
 - Uranium: Two charge states (33^+ , 34^+) before the stripper and five states ($76^+ \sim 80^+$) after that
- Two folding beam line in the tunnel
 - Front-end (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)



Progress of Beam Commissioning

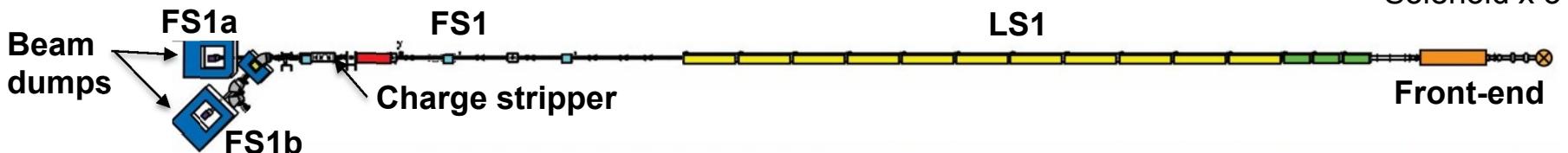
1st straight line was successfully completed

- Up to now, beam commissioning of the 1st straight section was completed.

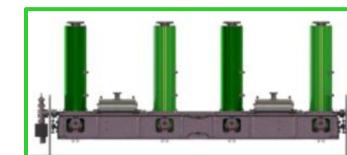
- August 2017: Front-end
- July 2018 : First three cryomodules in LS1
 - The diagnostic station (D-station) was constructed after the cryomodules
- March 2019 : LS1 and part of FS1
 - $3 \beta_{\text{OPT}} = 0.041$ and $11 \beta_{\text{OPT}} = 0.085$ cryomodules
- Completion is expected in 2021

The functions were successfully verified

- Four ion species of ^{40}Ar , ^{86}Kr , ^{20}Ne and ^{129}Xe accelerated more than 20 MeV/u
- Charge stripping by the carbon foil stripper
 - Liquid lithium stripper will be installed for high power

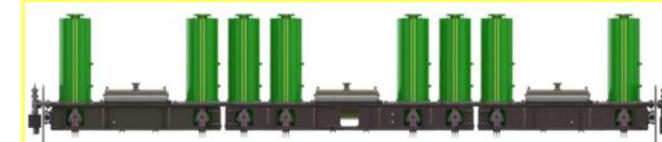


$$\beta_{\text{OPT}} = 0.041 \text{ cryomodule}$$



- QWR x 4
- Solenoid x 2

$$\beta_{\text{OPT}} = 0.085 \text{ cryomodule}$$



- QWR x 8
- Solenoid x 3

Four Ion Species Were Accelerated up to 20.3 MeV/u

- Detailed tuning was performed for $^{40}\text{Ar}^{9+}$

- Beam is accelerated to 20.3 MeV/u after 2π phase scan tuning of all resonators
 - » Beam energy is verified by Time-Of-Flight (TOF) measurement and 45° bending magnet field

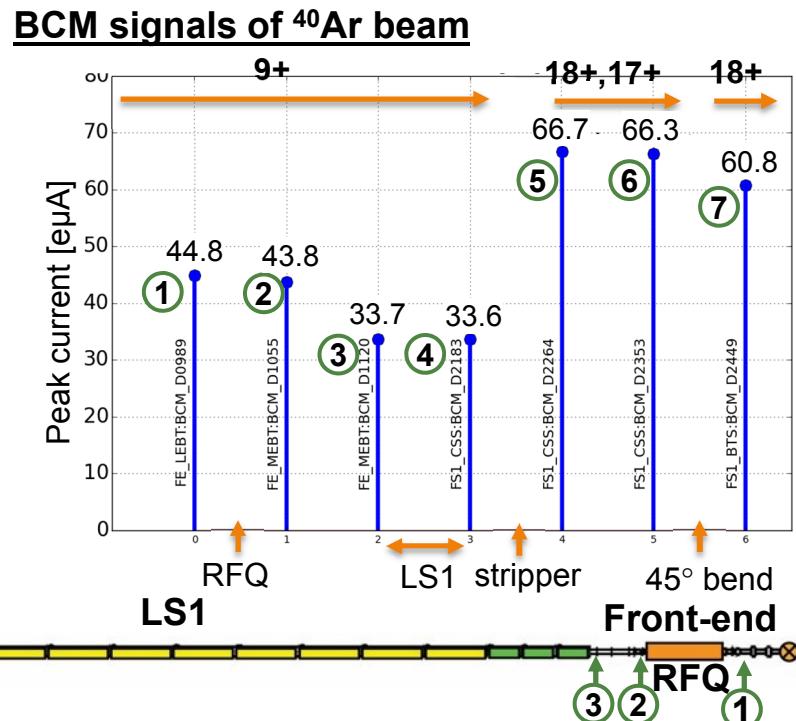
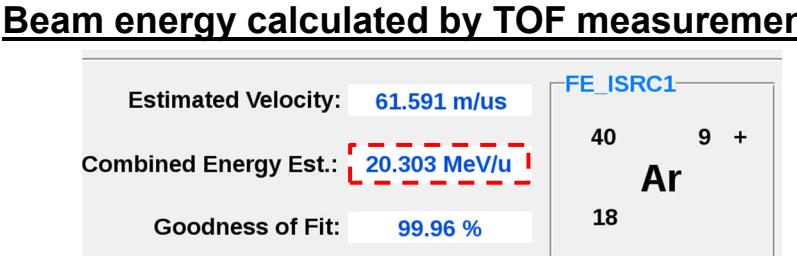
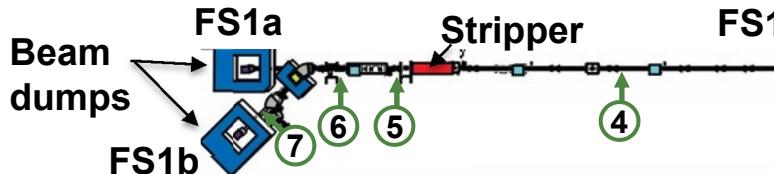
- Transverse matching in MEBT and FS1

- Other ion species, ^{20}Ne , ^{86}Kr , ^{129}Xe were accelerated up to 20.3 MeV/u

- All electromagnetic fields scaled by q/A ratio

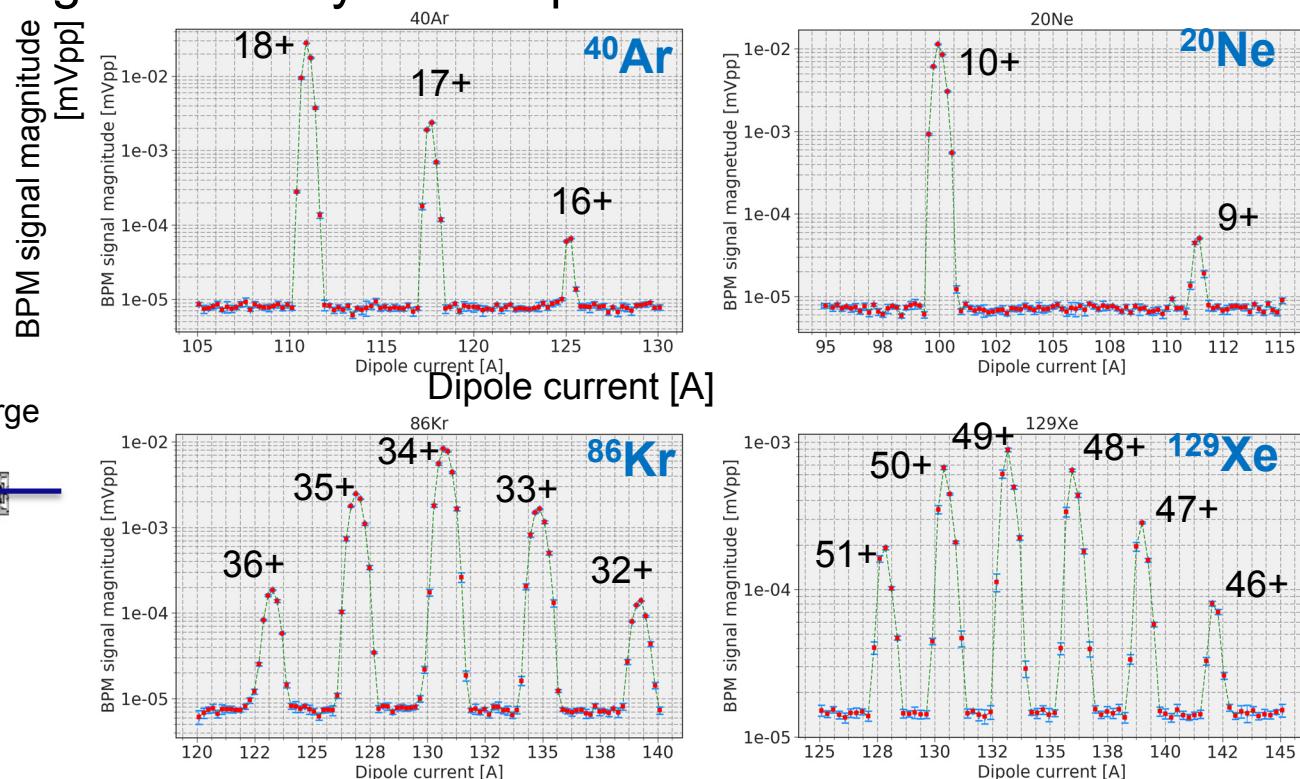
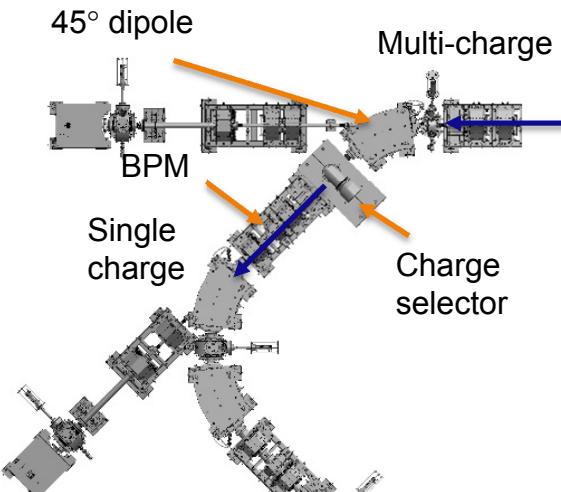
- 100% transmission is achieved from Medium Energy Beam Transport (MEBT) to the FS1

- 0.8 mg/cm² carbon foil was inserted on the beam line
- Beam current monitor (BCM) signals are averaged over several minutes



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

- 0.8 mg/cm² 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

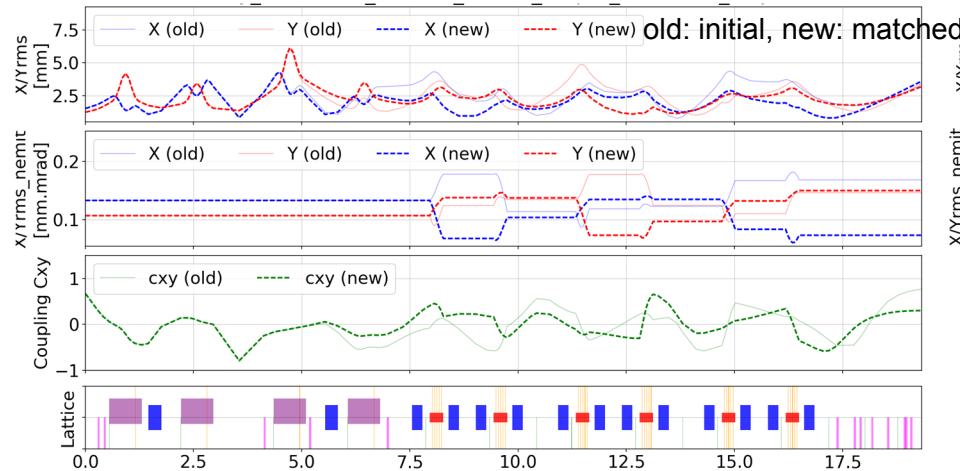


Transverse Beam Parameters are Consistent with Design Parameters

- 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

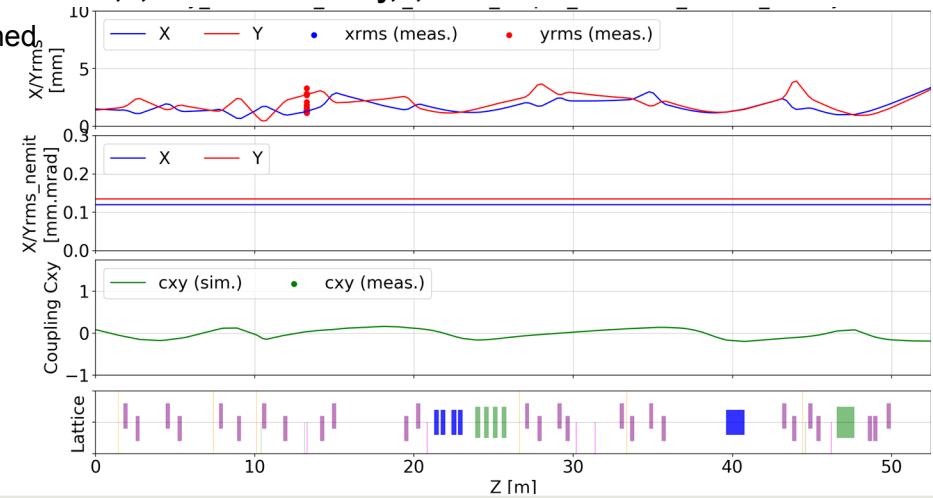
MEBT matching

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



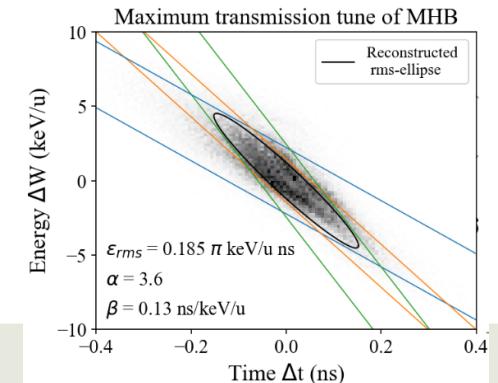
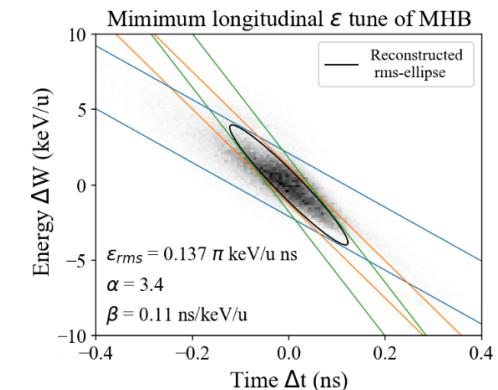
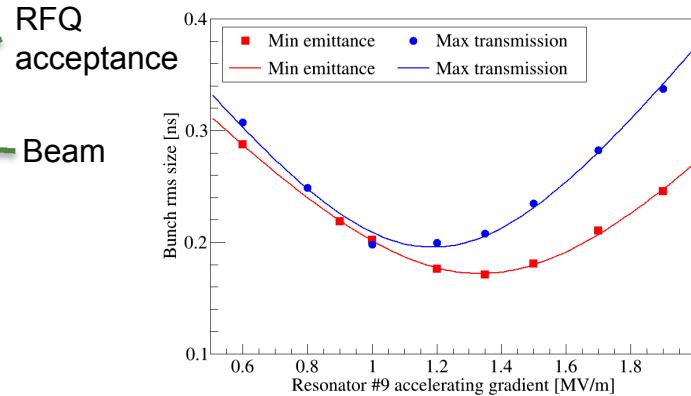
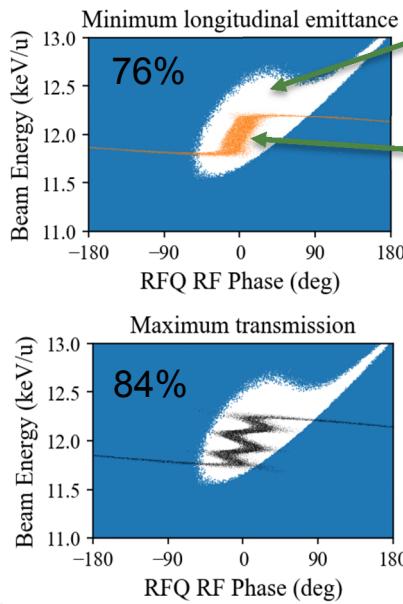
FS1 reconstructed envelope

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



Longitudinal RMS Emittance for Two MHB Settings

- The longitudinal emittance was measured by scanning RF amplitude of one SC resonator at bunching phase
 - ${}^{40}\text{Ar}$ beam accelerated to 1.0 MeV by the first seven resonators
 - Bunch length was measured by silicon detector in the D-station
- Measure the longitudinal emittance with two multi harmonic buncher settings
 - Minimum longitudinal emittance
 - Maximum beam transmission



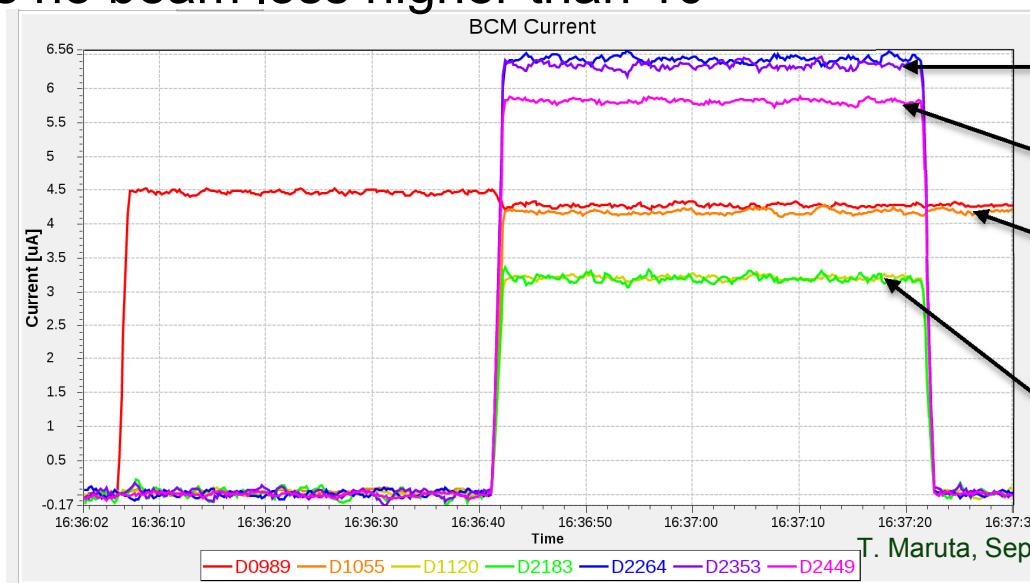
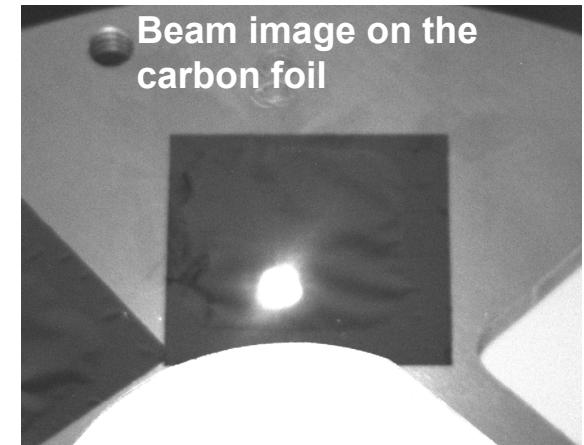
$[\pi\text{keV/u nsec}]$	Meas.	Sim.
Min. emit.	0.14	0.12
Max. trans.	0.19	0.14

Demonstration of ^{40}Ar High Power Operation 100% Beam Transmission

- Two types of high power operation was demonstrated for 1 minutes

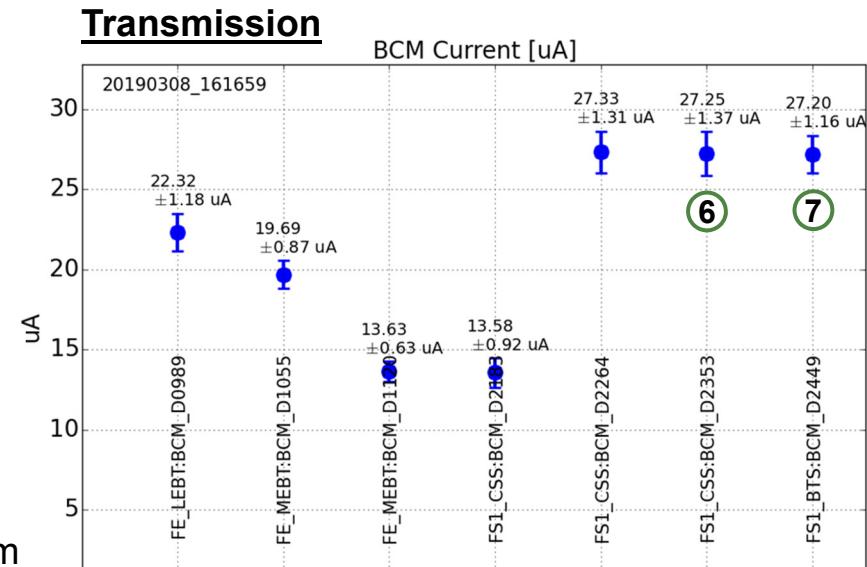
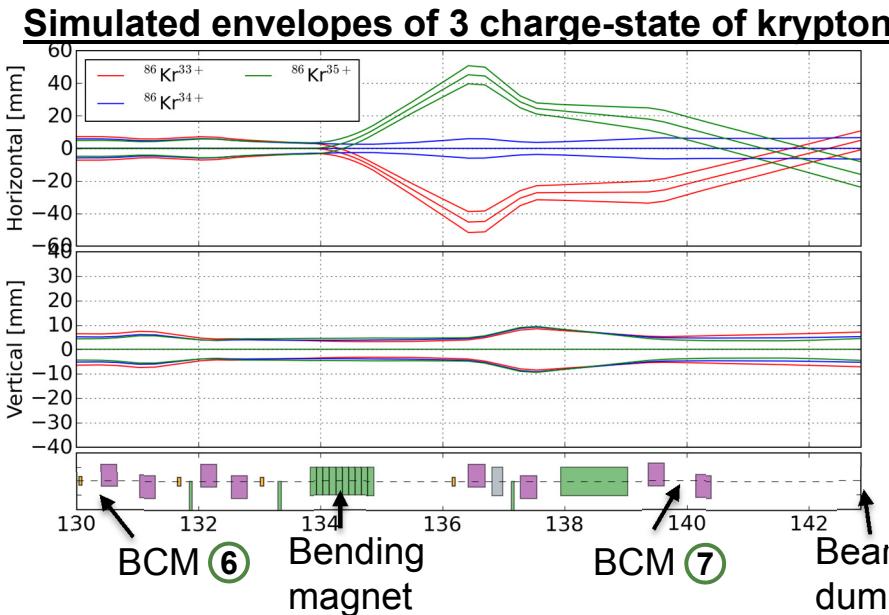
Ar9+	I [euA]	Beam duty
High current	133	3%
High duty	3.2	100%

- 133 euA is corresponding to 31% of design current
- Beam power limited by the beam dump capacity
- 100% transmission and no beam loss in LS1
- There is no beam loss higher than 10^{-4}



Three Charge States of Krypton (33+, 34+, 35+) Beam Were Transported to the FS1b

- FRIB is designed to accelerate multi charge states
 - Example: 76+ ~ 80+, $\Delta q/q = 6.4\%$, of uranium beam after the stripper
- Three charge states, 33+ to 35+ ($\Delta q/q = 5.9\%$), of krypton beam are generated on the foil
- All charge states are transported after the 45° bend
 - Beam transmission is ~100%



^{86}Kr Two Charge States Acceleration

Capability of LS1 Dual Charge States Acceleration Demonstrated

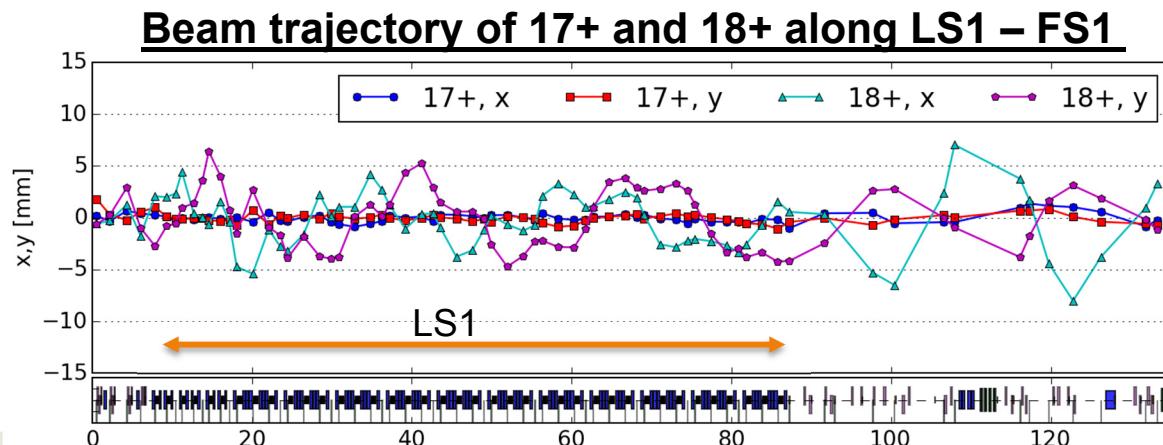
- Charge difference is twice of Uranium beam
 - Beam is more mismatched than design
- Everything is tuned for $^{86}\text{Kr}^{17+}$
 - Beam trajectory aligned within ± 1 mm
 - Transverse matching was conducted at the FS1 entrance
- ECR IS and LEBT are tuned to $^{86}\text{Kr}^{18+}$ because a velocity 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
- 100% transmission in LS1

$^{86}\text{Kr}^{17+,18+}$

$^{238}\text{U}^{33+,34+}$

$$\frac{\Delta q}{q} = 5.7\%$$

$$\frac{\Delta q}{q} = 3.0\%$$

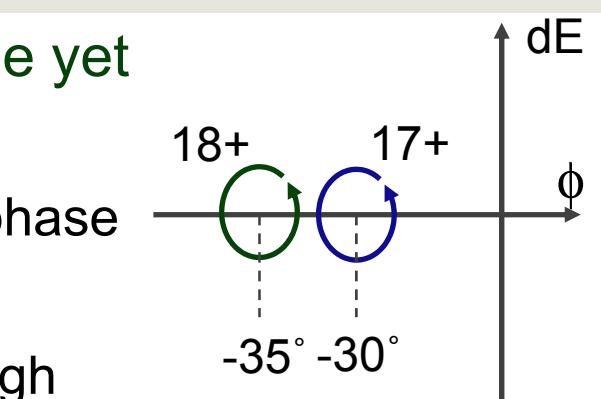


⁸⁶Kr Two Charge States Acceleration in LS1

Longitudinal Motion

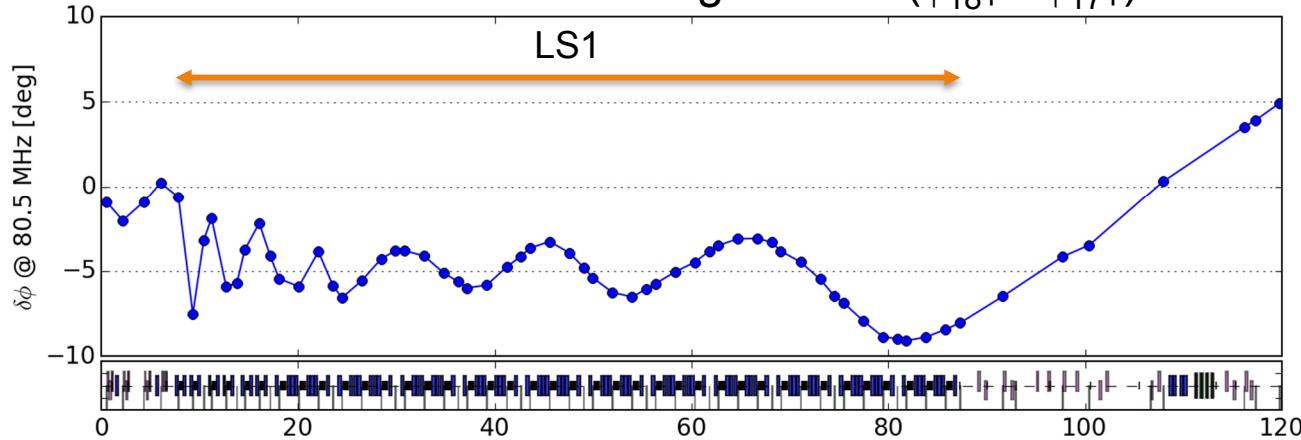
- Velocity equalizer before the RFQ is not available yet
- 18+ is ~5 degree earlier than 17+ for entire LS1
 - Both charge states stay around their synchronous phase
- Energy difference at the LS1 end is very small
 - Beam centroid on the charge selector is close enough for selection

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

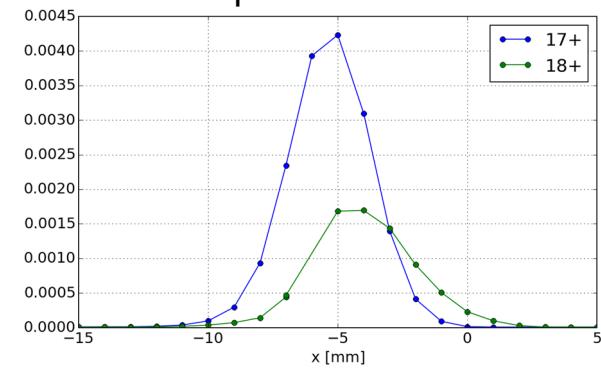


$$q_{18+} \cos(\phi_{18+}) = q_{17+} \cos(\phi_{17+})$$

Phase difference of two charge states ($\phi_{18+} - \phi_{17+}$)



Horizontal profile at the selector



[mm]	17+	18+
Center	-5.34	-3.93
RMS	1.68	2.18



Facility for Rare Isotope Beams
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Summary

- Beam commissioning of FRIB Front-end to the 1st straight section was completed
- Main functions of the section is verified
 - Four ion species are accelerated up to 20.3 MeV/u
 - Charge stripping and charge state selection were successfully demonstrated
- Further studies were also done successfully
 - No significant transverse emittance growth happened after MEBT matching
 - Longitudinal phase space distribution is close to the design
 - 100% transmission during high power test of high intensity and high duty
 - The capability of multi charge state accelerations were demonstrated by ⁸⁶Kr

Acknowledgments

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