Completion of FRIB Beam Commissioning

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On Behalf of FRIB Accelerator Team

LINAC conference, Liverpool, August 29, 2022

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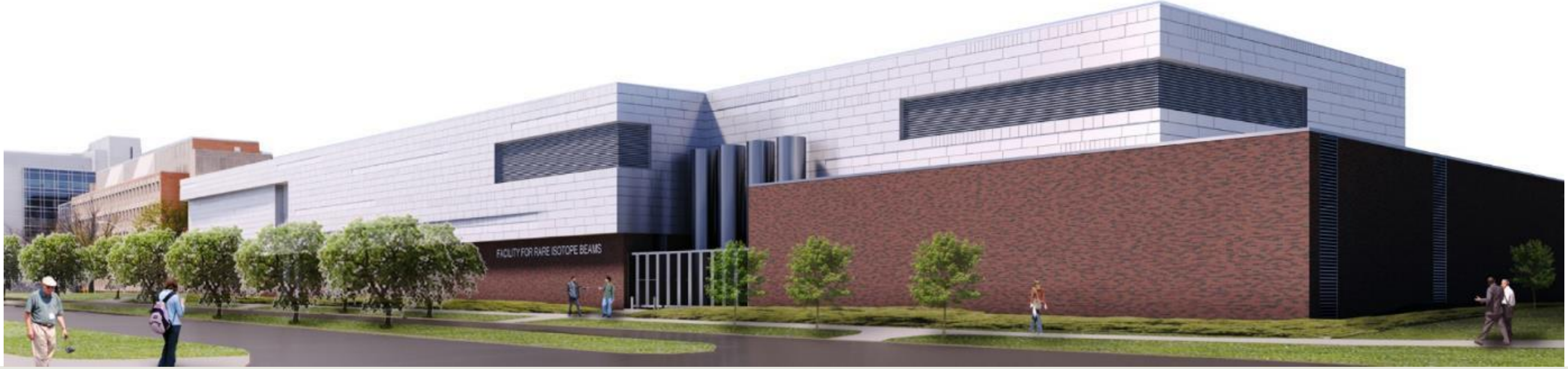
Outline of the Talk

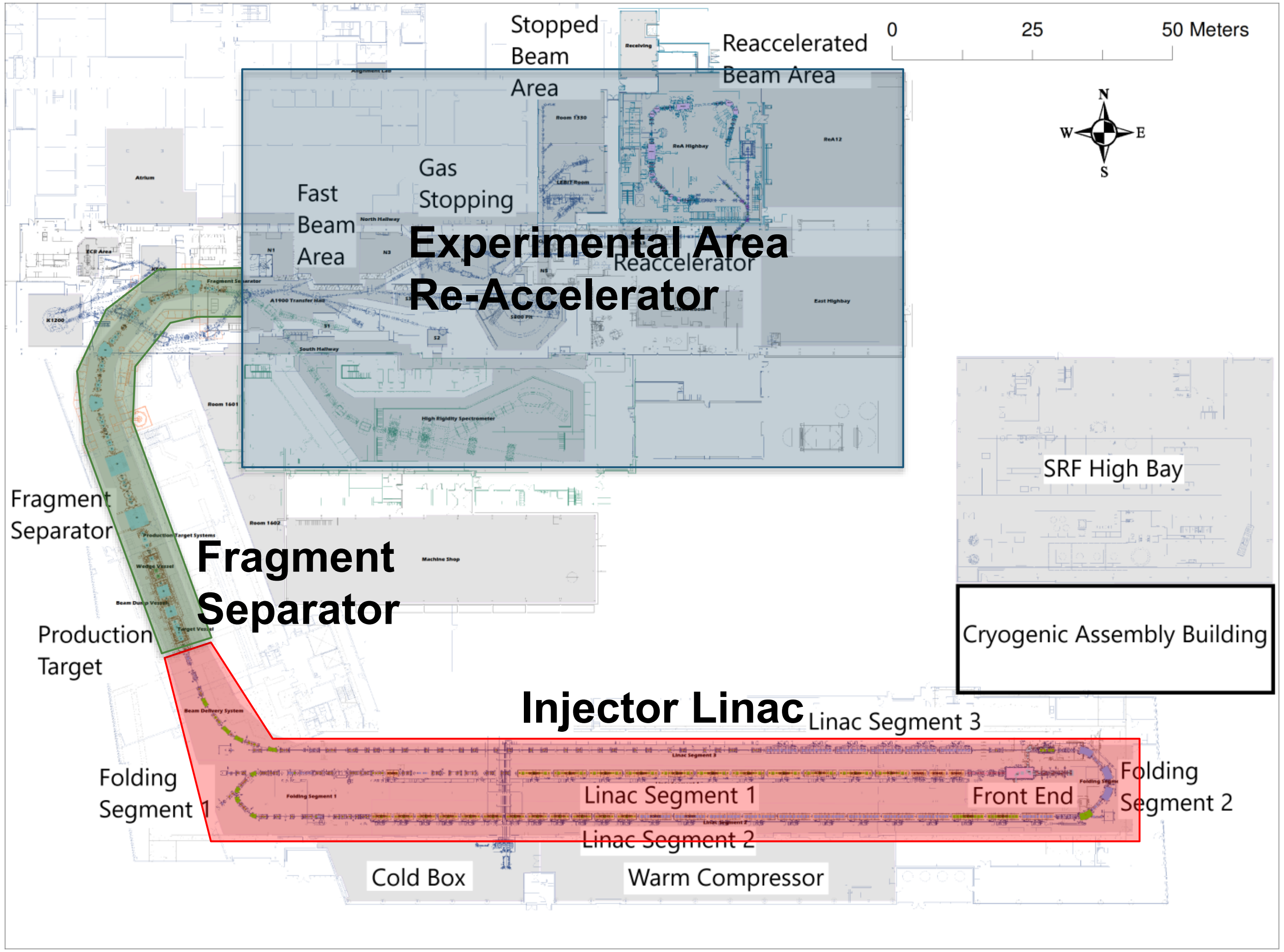
- Introduction
- Outline of FRIB driver linac
- Beam study results and development of high level applications
- Experiences with 1 kW user operations
- Conclusion

FRIB Construction Completed in Jan. 2022 On Cost and Five Months ahead of Schedule

- FRIB Project built a $730 million national user facility funded by the U.S. Department of Energy Office of Science (DOE-SC)
  - Additional funding was available from the Michigan State University, and the State of Michigan
- FRIB construction completed in January 2022, on cost and five months ahead of schedule
- FRIB is now a DOE-SC scientific user facility for rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC



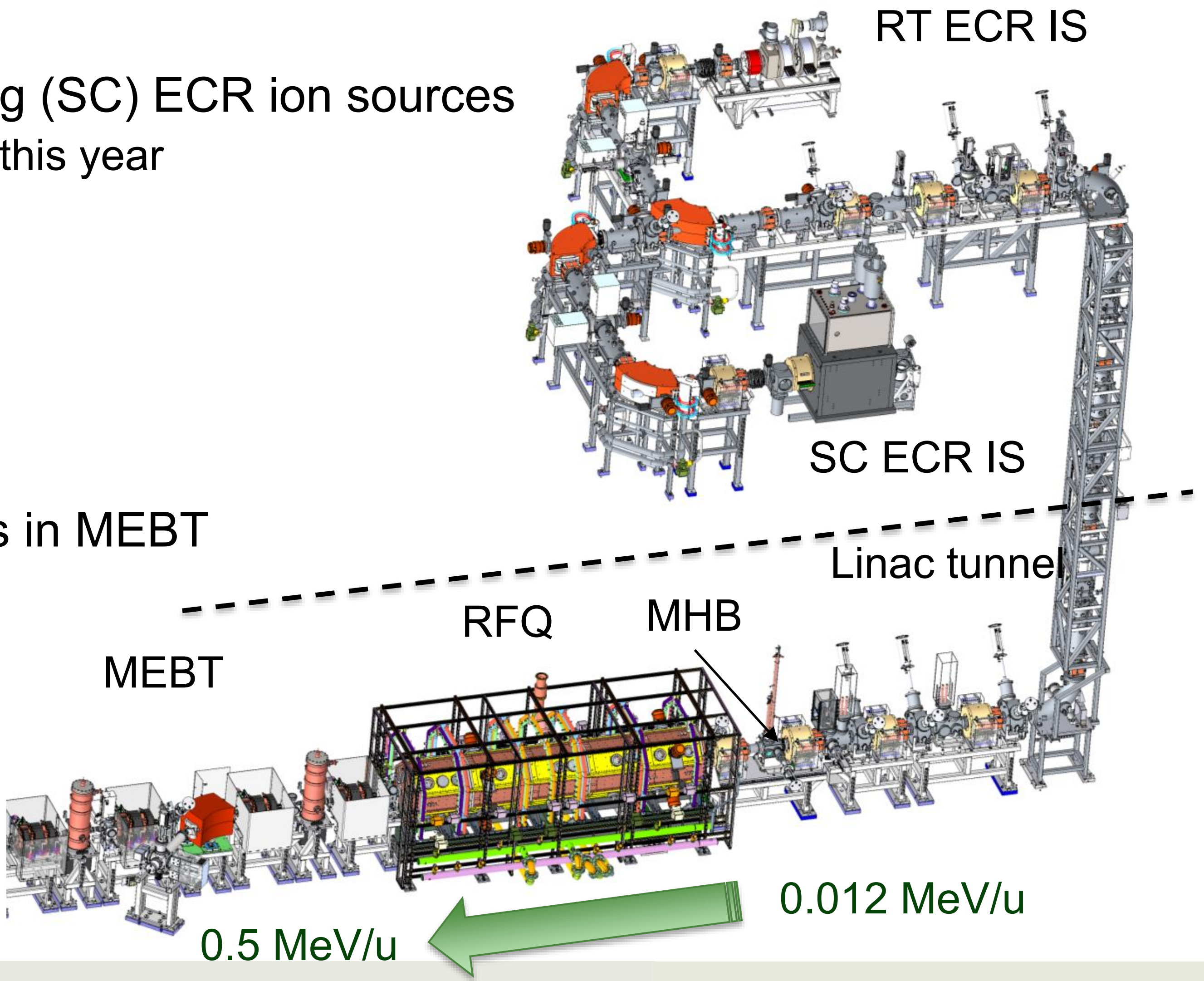
Facility for Rare Isotope Beams at Michigan State University



- Includes injector linac, fragment separator, experimental area
- Driver linac provides 400 kW primary beam of stable isotopes to the fragmentation target
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - Beams of all elements and short half-lives
  - Fast, stopped, and reaccelerated beams

FRIB Front End

- FRIB Front-end consists from
  - Room Temperature (RT) and Super Conducting (SC) ECR ion sources
    - » Beam commissioning of SC ECR will start end of this year
  - 90 kV accelerating tube
  - Charge selection system
  - Low Energy Beam Transport (LEBT)
  - Radio-Frequency Quadrupole (RFQ)
  - Medium Energy Beam Transport (MEBT)
  - Multi-harmonic buncher (MHB) and rebunchers in MEBT
  - Beam diagnostics
- Designed to transport ions in 1/2 (^{4}He) ≥ q/A ≥ 1/7 (^{238}U)
- Capability to transport two charge states in Future upgrade

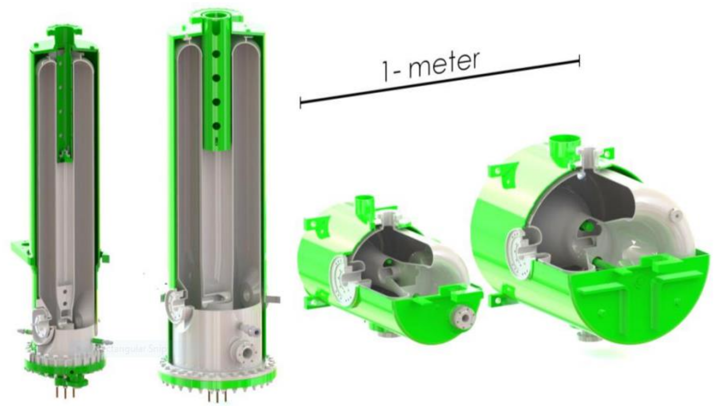


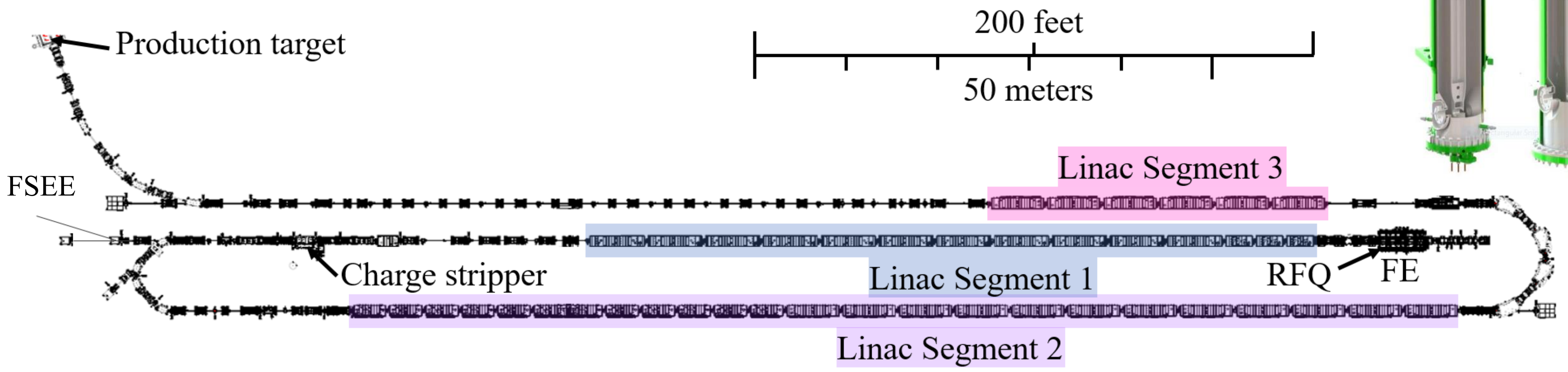
Outline of FRIB Injector Linac

- Three super-conducting (SC) linac segments (LS1~3)
  - 4 types of 324 SC cavities
- Charge stripper is located after LS1
  - Liquid Lithium stripper and Rotating carbon stripper
- Capability of simultaneous multi-charge state beam acceleration
  - ^{238}U: 33+, 34+ from ECR ion source to the charge stripper
    76+ ~ 80+ after the stripper
  - Both achromatic and isochronous conditions for bending sections

Super-conducting cavity

β=0.041	β=0.083	β=0.29	β=0.53
QWR		HWR	
80.5 MHz		322 MHz	
12	92	72	148

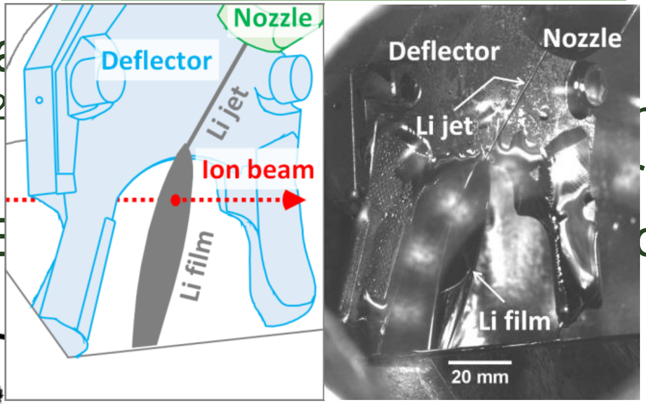




Outline of FRIB Injector Linac

- Three super-conducting (SC) linac segments (LS1~3)
  - 4 types of 324 SC cavities
- Cha… after LS1
  - Liq… Rotating carbon stripper
- Ca… multi-charge state beam acceleration
  - 2… n source to the charge stripper
    …ripper
  - E… onous conditions for bending sections

Liquid Lithium stripper:
TH1AA05 by Kanemura



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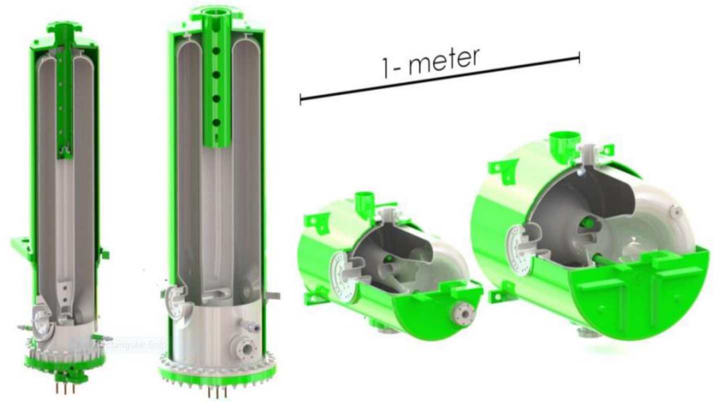

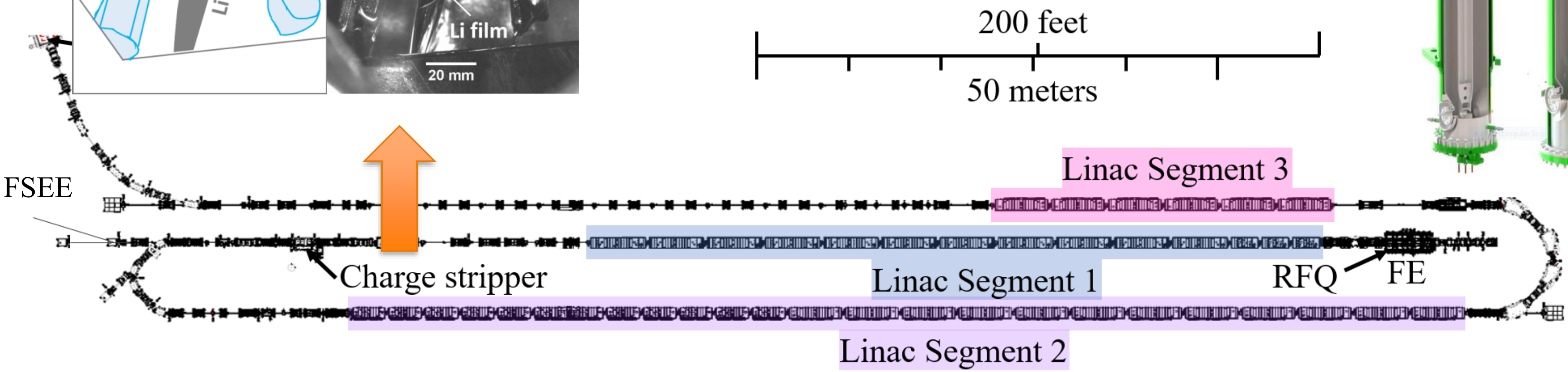

Outline of FRIB Injector Linac

- Three super-conducting (SC) linac segments (LS1~3)
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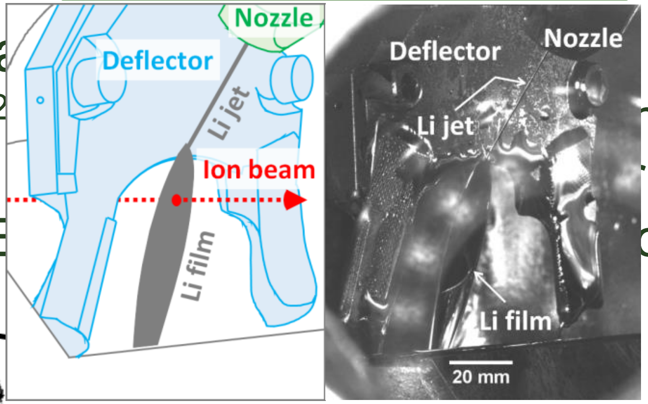
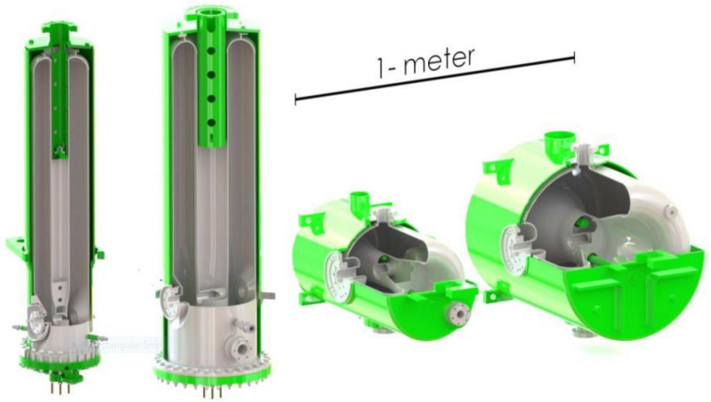
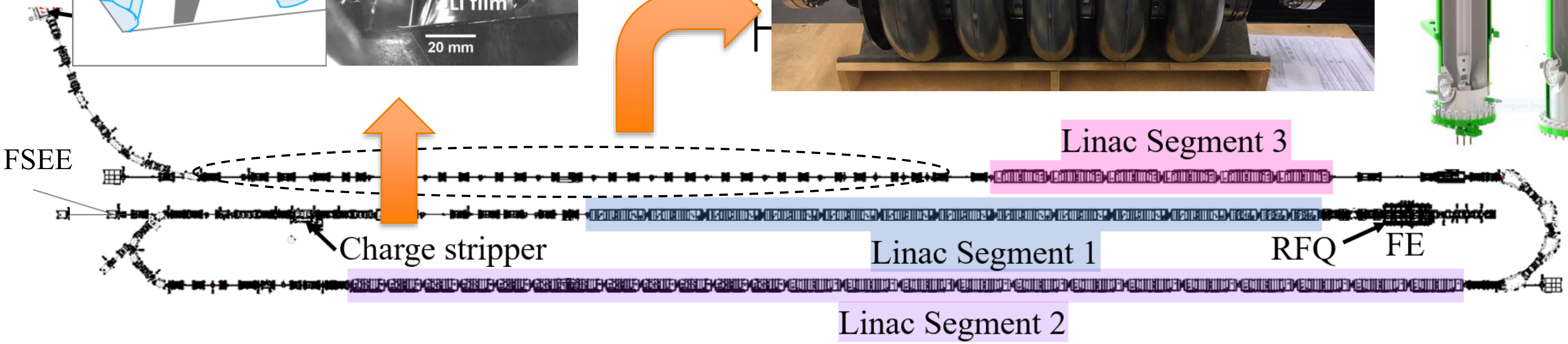


Energy Upgrade: TH1AA02 by McGee

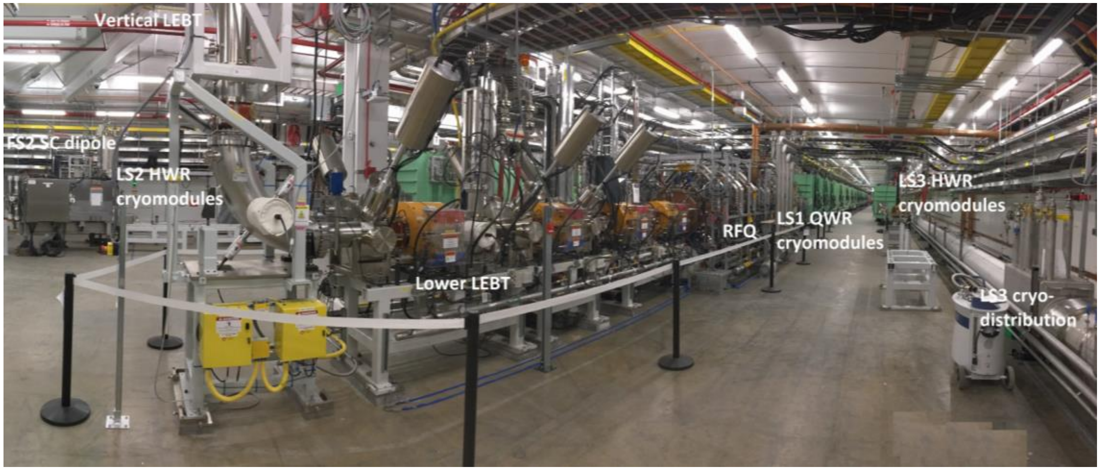
Super-conducting cavity

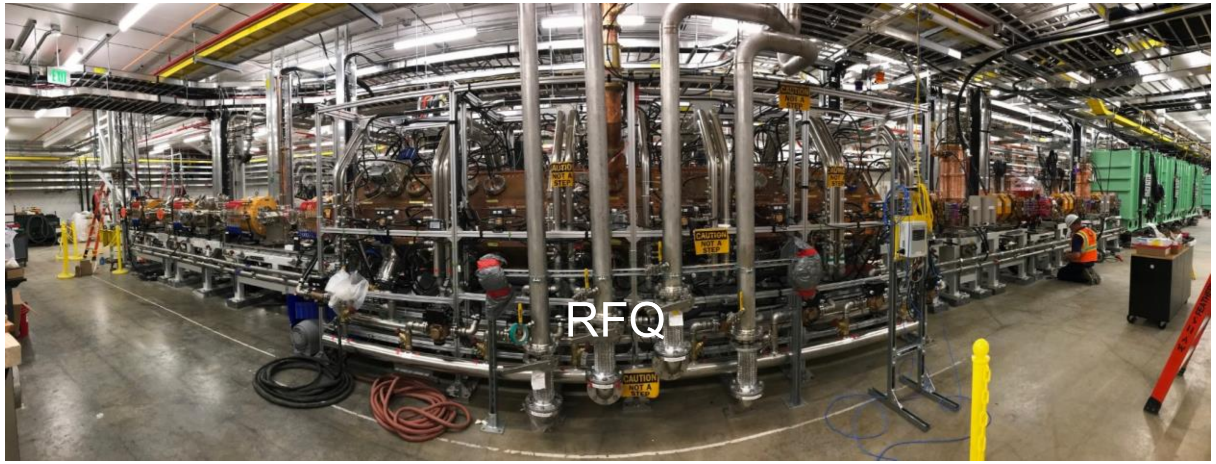
β=0.041	β=0.083	β=0.29	β=0.53
QWR		HWR	
80.5 MHz		322 MHz	
12	92	72	148

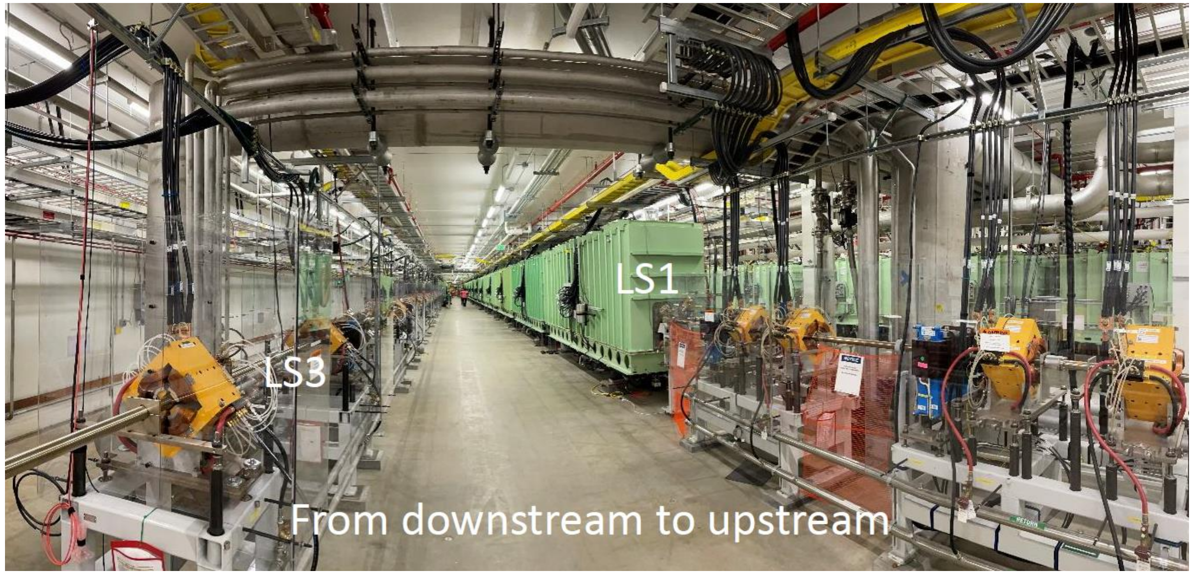




Pictures in the Linac Tunnel







Main Results of Beam Commissioning

FRIB threshold key performance parameter	Date
Measure FRIB driver linac ^{36}Ar beam with energy larger than 200 MeV/u and a beam current larger than 20 pnA	Mar 2020
Detect and identify ^{84}Se isotopes in FRIB fragment separator focal plane	Dec 2021
Measure reaccelerated rare isotope beam energy larger than 3 MeV/u	Sep 2015

2017 | 2018 | 2019 | 2020 | 2021 | 2022

April 2017
1st beam observed
LEBT 0.012 MeV/u

July 2017
RFQ acceleration
0.5 MeV/u

May 2018
1st acceleration by SC cavities
2.0 MeV/u

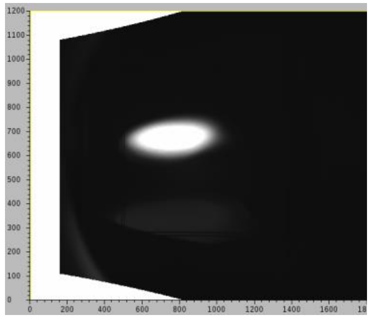
Feb. 2019
LS1
20 MeV/u
Charge stripping

Mar 2020
LS2
^{36}Ar 204 MeV/u

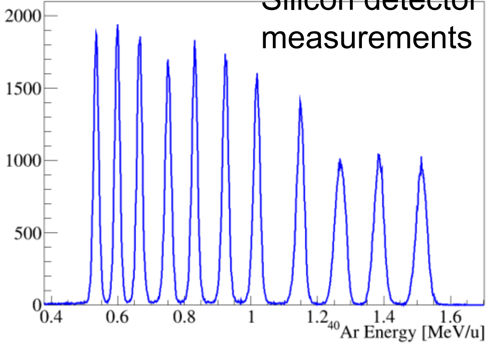
Apr 2021
LS3
^{86}Kr 212 MeV/u

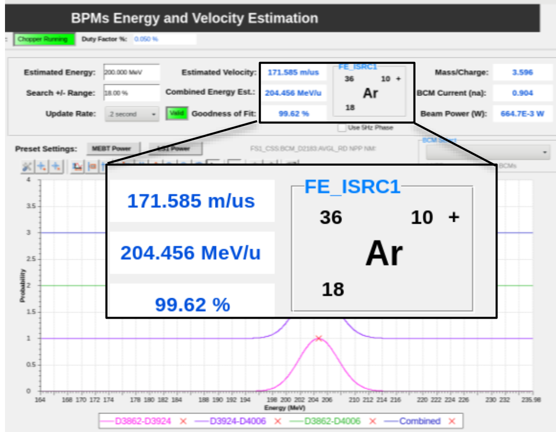
Dec 2021
Beam reached to Fragment separator

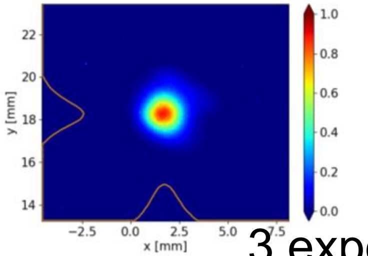
May 2022
Ribbon-cutting ceremony



Silicon detector measurements



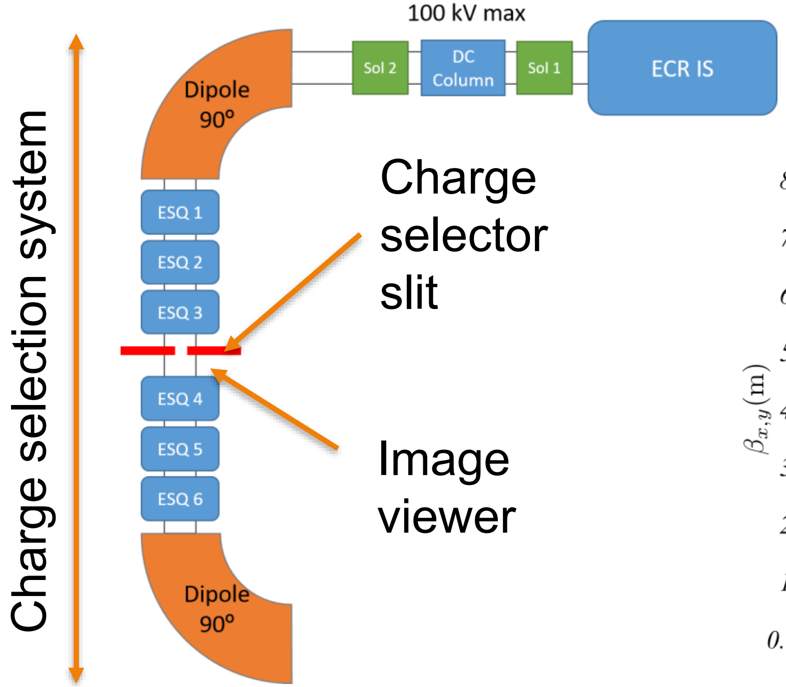


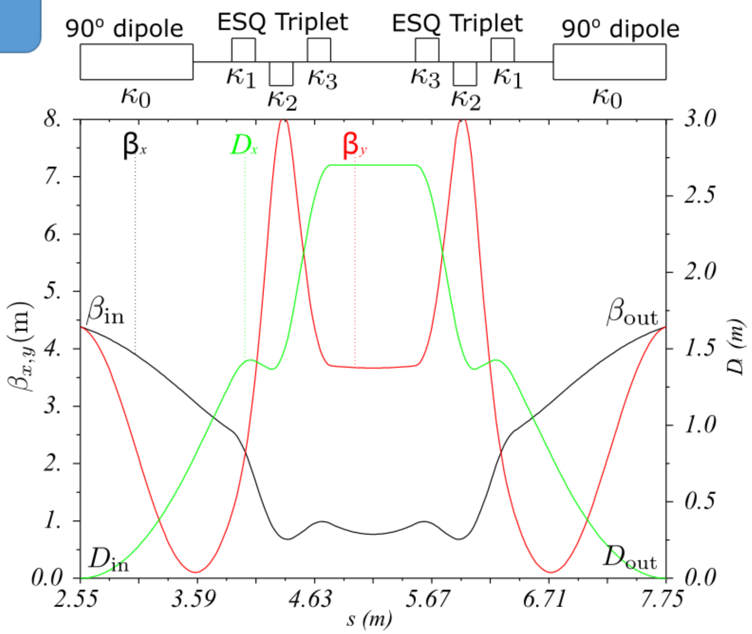


3 experiments are successfully completed with 1 kW beam
^{48}Ca, ^{82}Se, ^{70}Zn

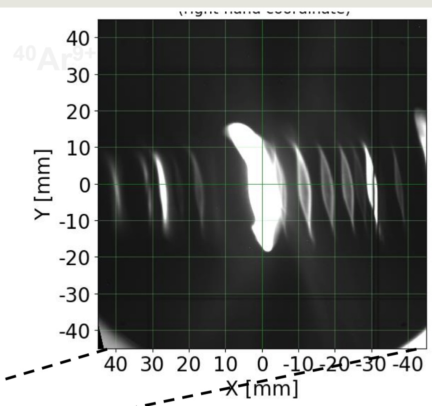
Elimination of Beam Contaminants from ECR Ion Source

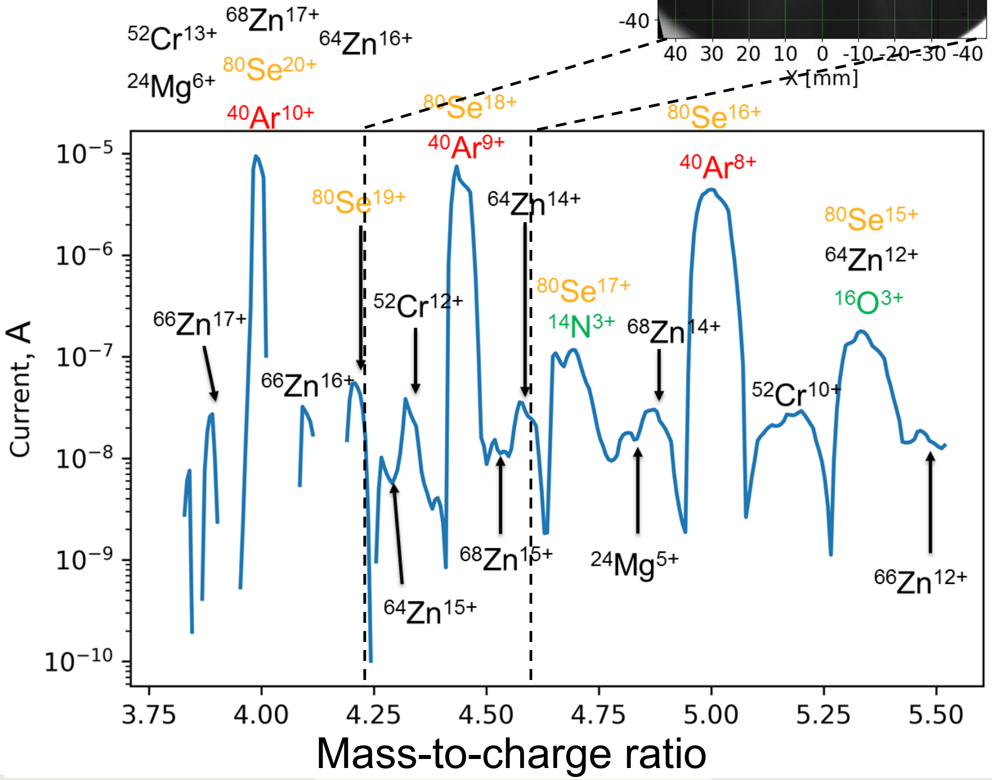
- Ion beam of interest is selected by the charge selection system from the various ions species simultaneously extracted from ECS IS
- Charge selection resolution is about 1%





- ^{40}Ar: beam ion
- ^{16}O: plasma support gas
- ^{14}N: atmosphere
- ^{80}Se: previous run
- Zn, Cr and Mg: plasma chamber material

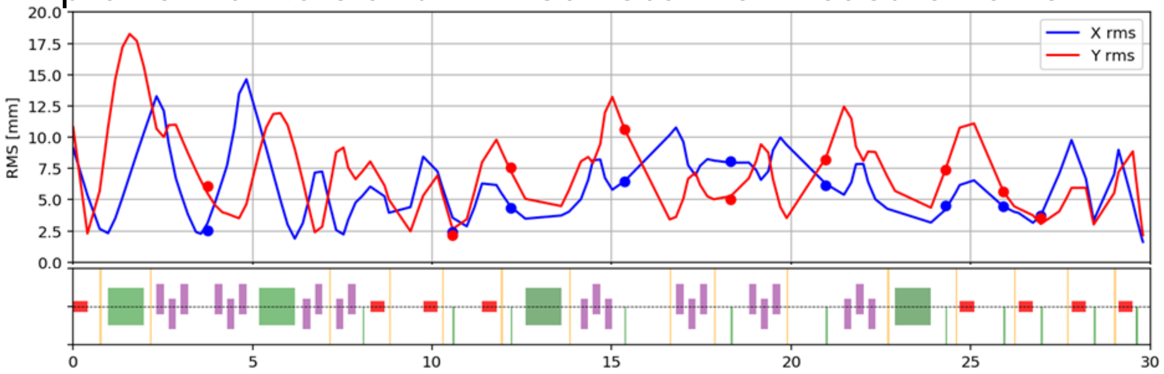




LEBT Beam Profiles

- Various kinds of diagnostic tools are available for profile measurement
- Intensive beam study has been conducted with ^{40}Ar to establish LEBT optics
  - Analysis scripts for Allison scanner, PM and image viewer were developed
  - FLAME (matrix) and TRACK (PIC) models are developed for
- Snapshots of image viewers and a TRACK simulation are agreed well

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



TRACK simulation

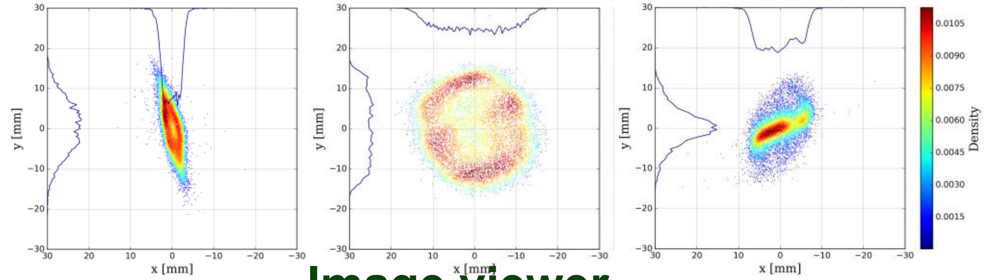
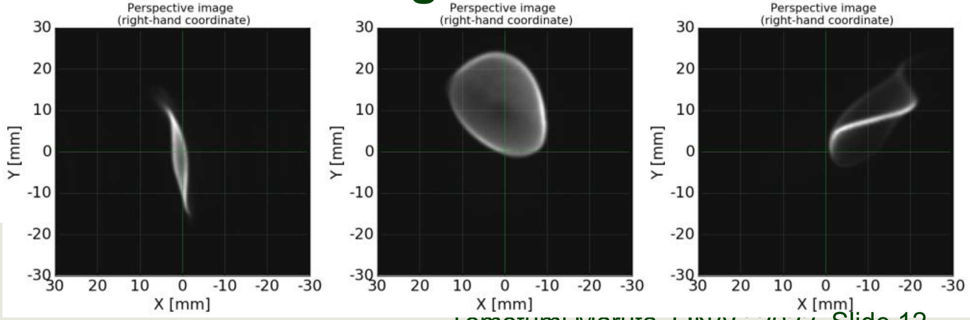
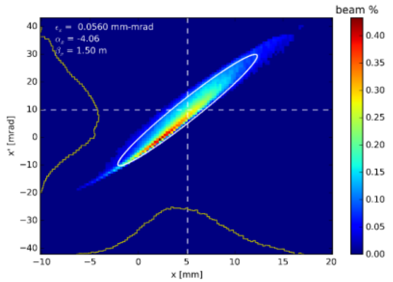


Image viewer

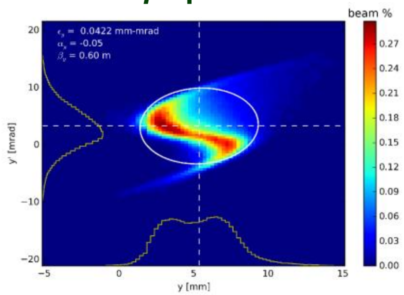


Allison scanner

X-Xp plane



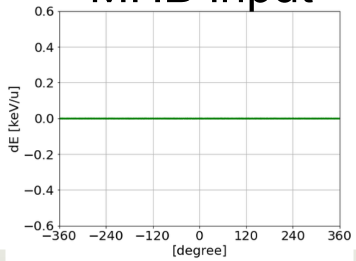
Y-Yp plane



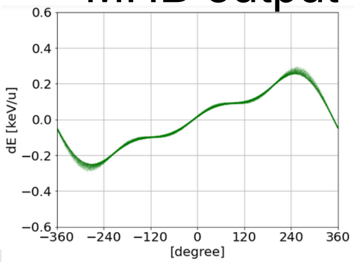
Beam Acceleration in Radio Frequency Quadrupole
Beam Transmission is as Design

- In July 2017, RFQ was tested with ^{40}Ar beam (q/A = 1/4) and verified beam transmission is as design
- In September 2020, the heaviest ion of ^{238}U beam (q/A = 1/7) is successfully accelerated with beam transmission of 82%
  - Multi-Harmonic Buncher (MHB) forms very small longitudinal emit.

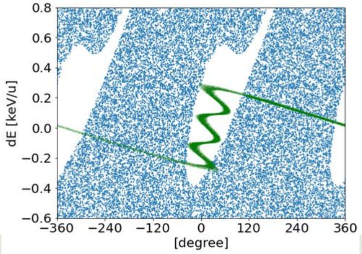
MHB input



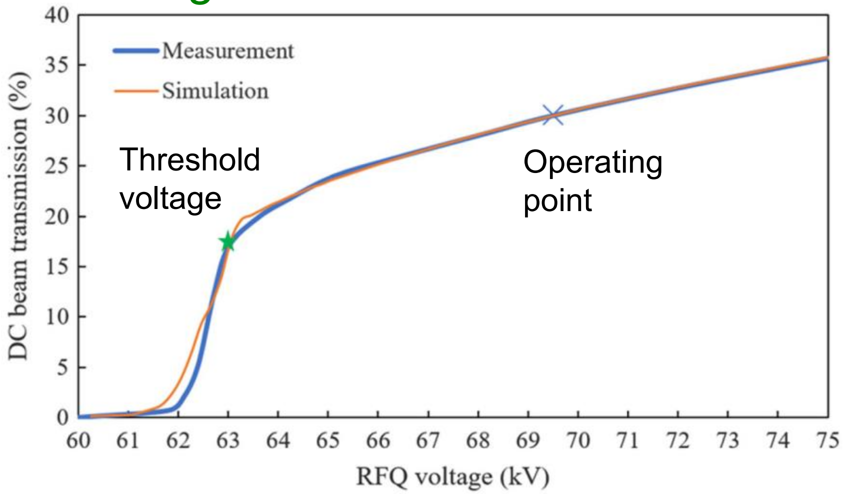
MHB output

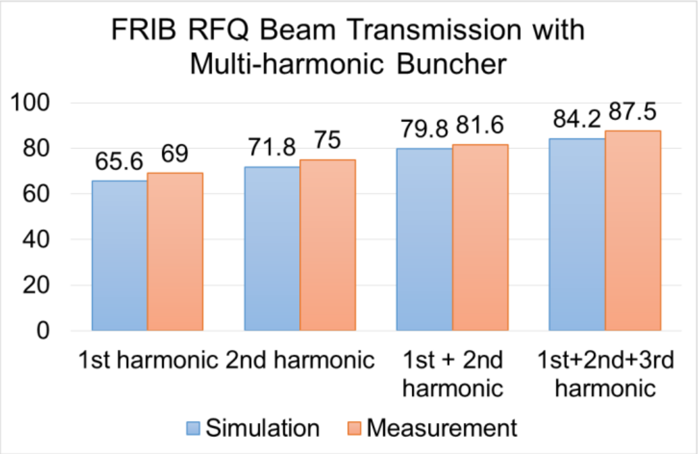


RFQ input



RFQ voltage vs. DC beam transmission

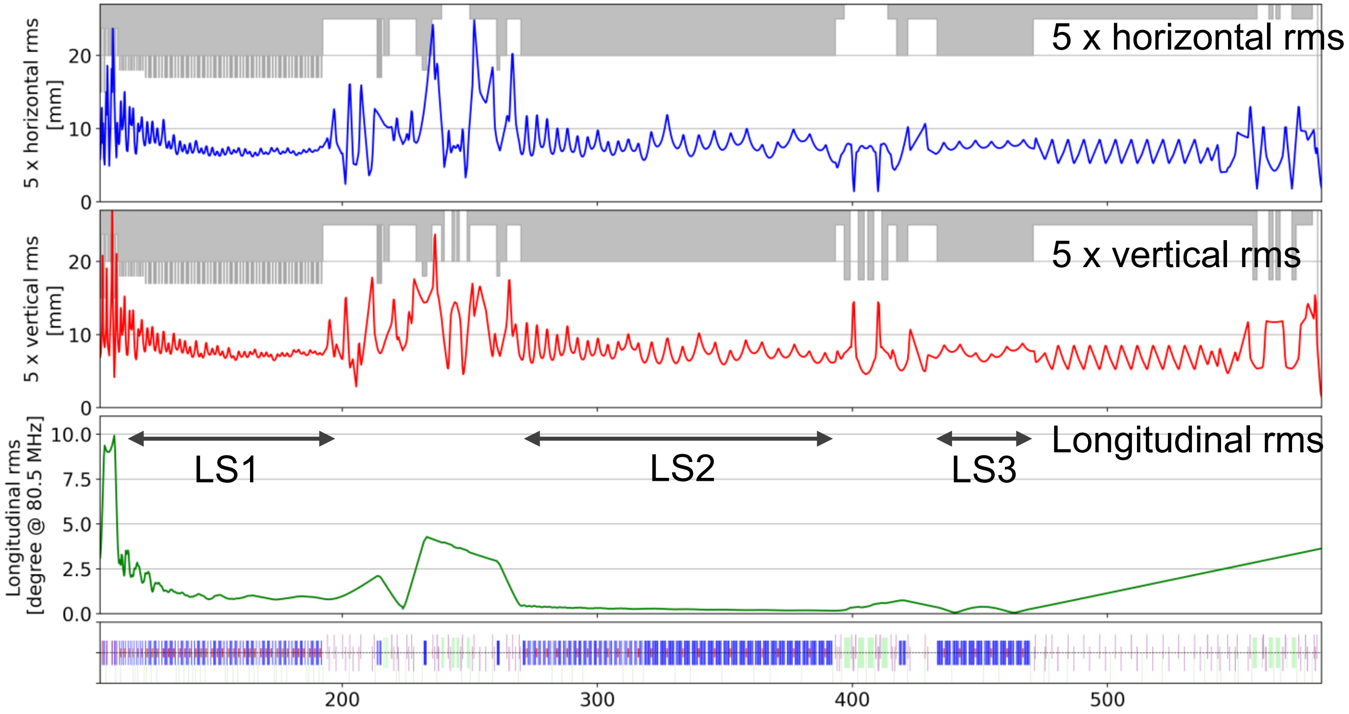


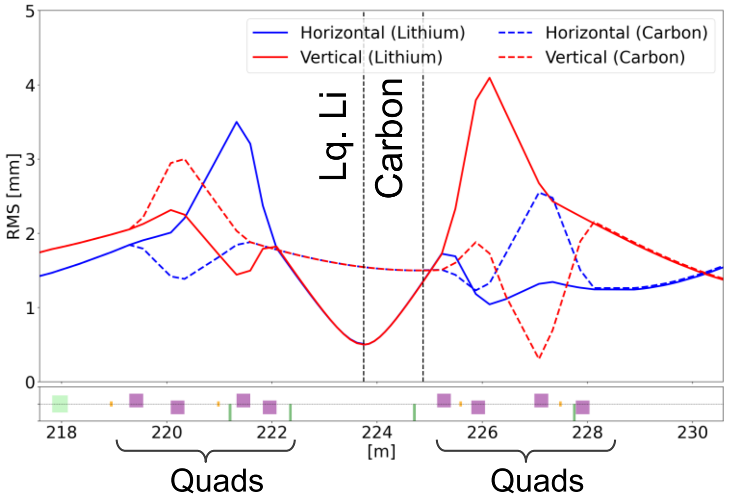


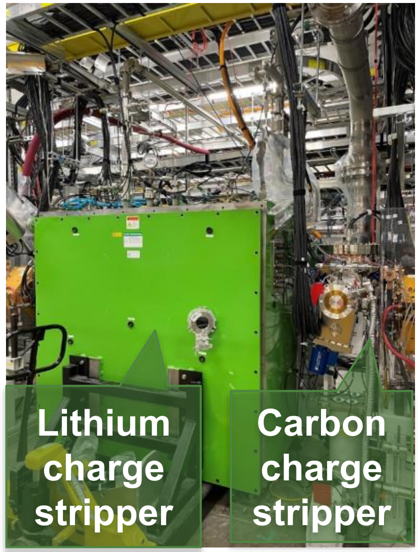
Phys. Rev. Accel. Beams 22, 040101

Reference Optics Established by 3D Computer Model for Entire Linac

- Designed beam envelope from MEBT to the Fragment separator by envelope code (FLAME)
  - Aperture of linac sections are more than 7 times of rms beam size
- Enable to switch Lq. Lithium and rotating carbon foil by tuning 4+4 quadrupoles
- Scale magnets by magnetic rigidity depending on beam ion and energy



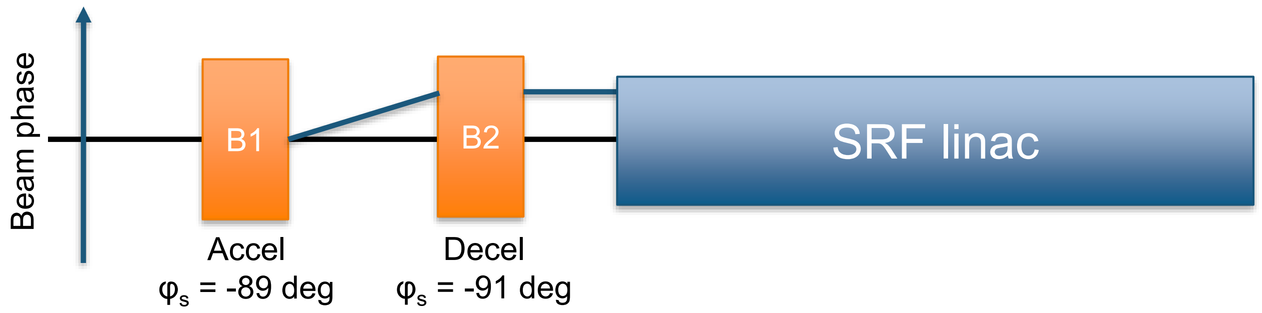




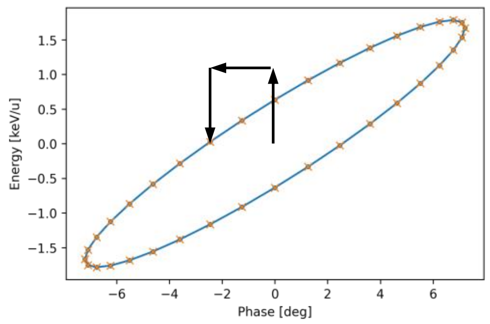
Emittance	Before foil	After foil
Transverse [mm-mrad]	0.12	0.15
Longitudinal [ns-keV/u]	0.2	0.3

Longitudinal Envelope Mapping

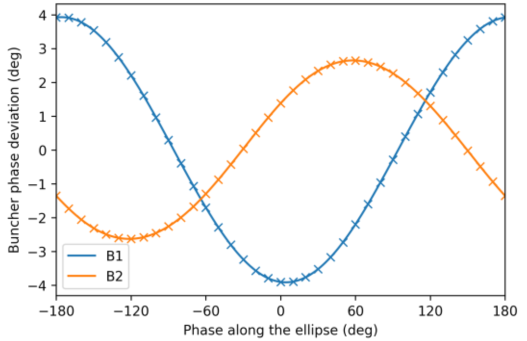
- Longitudinal envelope is measured by envelope mapping method
  - Beam centroid is kicked by MEBT bunchers so that longitudinal beam centroid is placed on the matched ellipse
  - Adjust the buncher setting and measure the BPM response to steered beam

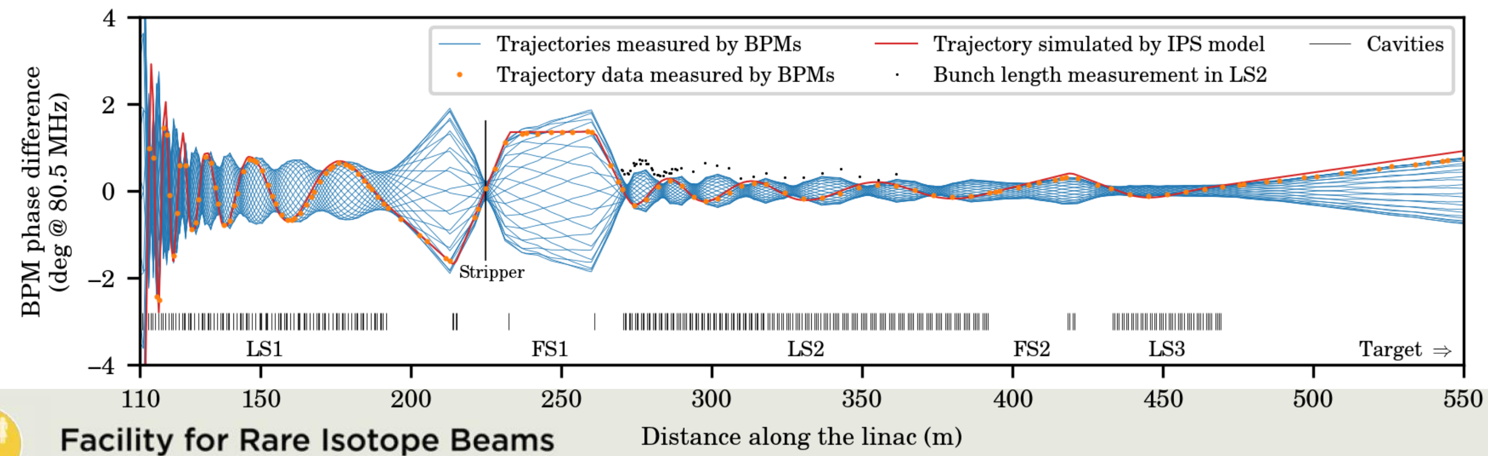


Beam ellipse at the SRF linac entrance



Adjustment of MEBT bunchers

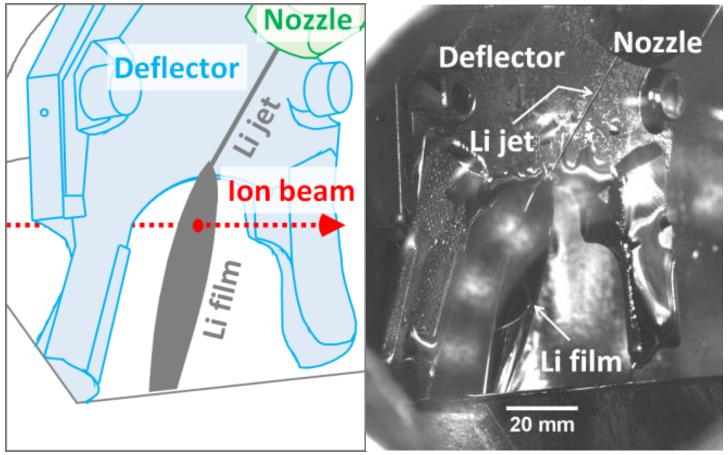


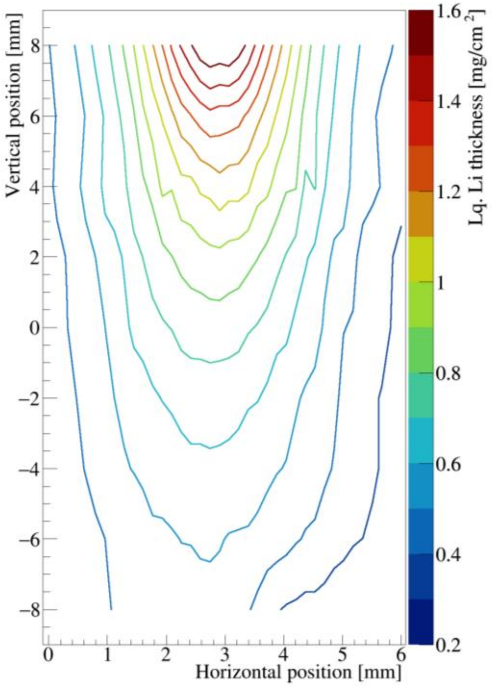


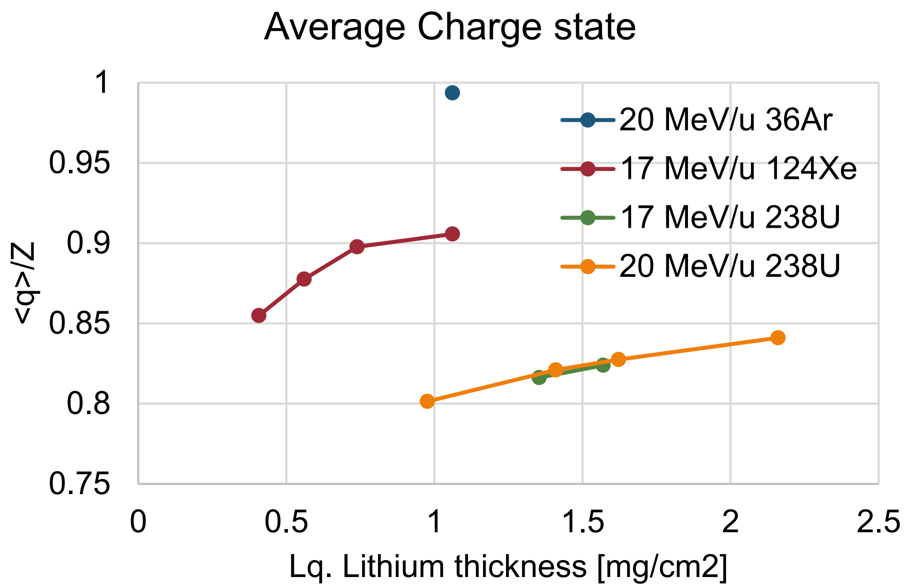
Lq. Lithium Charge Stripping of Ar, Xe and U Beams Successfully Demonstrated

Phys. Rev. Lett. 128. 212301 (2022)
TH1AA05

- Film thickness distribution was measured and verified that the uniformity is enough for 0.5 mm rms beam
  - Energy loss is calculated by Time-of-Flight measurements before and after the foil
  - Convert energy loss to thickness based on SRIM calculation
- Average charge states measured by scanning downstream dipole. The thickness of liquid lithium film can be moved with respect to the beam to optimize the thickness.



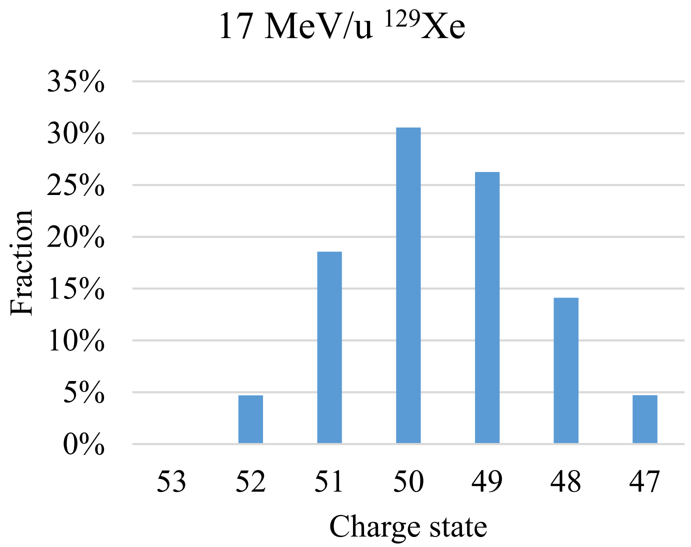




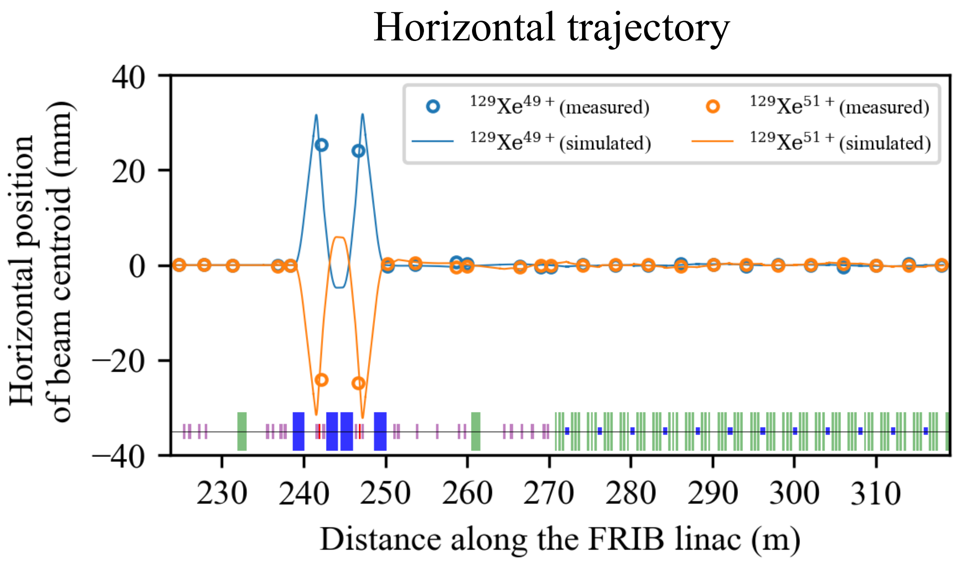
Acceleration of Three Charge States of ^{129}Xe 2.5 Times Increase of Beam Intensity

- FRIB is designed to accelerate multiple charge states simultaneous to increase beam power
  - For 129Xe beam, 3-charge-state acceleration increases intensity by 2.5 times
- Multi-charge beam phase space is recombined after the dispersive magnetic system

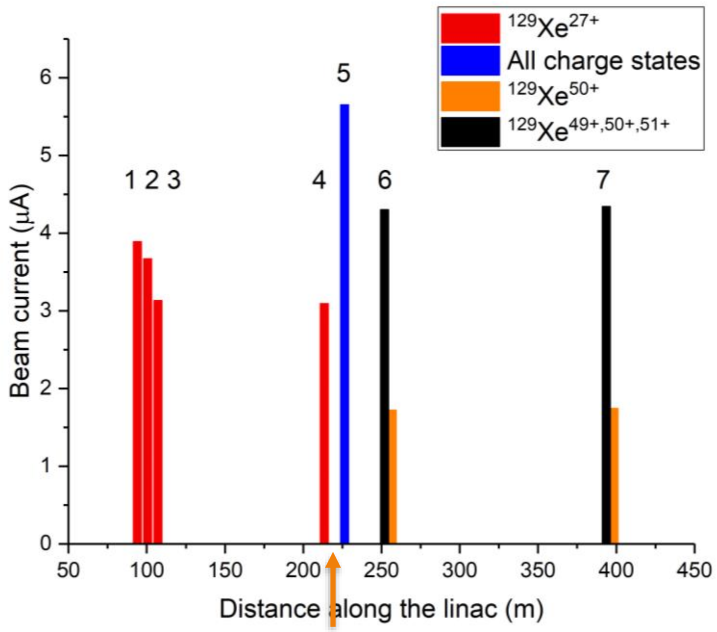
Charge state distribution
after carbon stripper



50+	31%
49+, 50+, 51+	77%

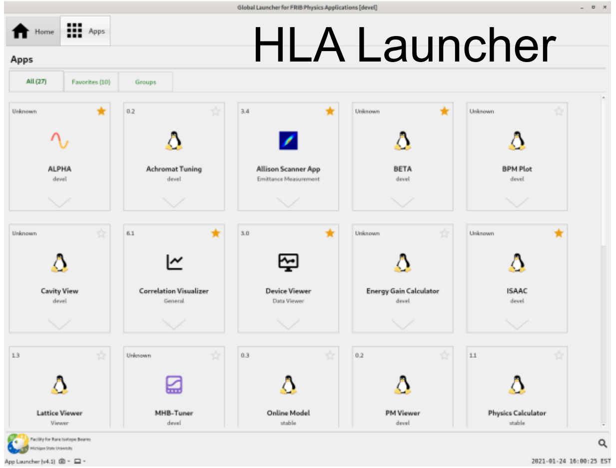


Beam current monitor



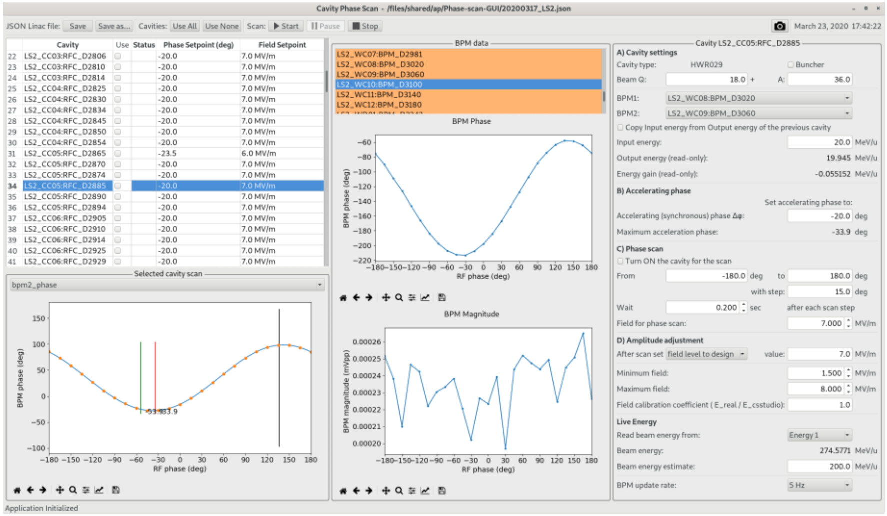
High Level Applications (HLA) Have Been Developed for Efficient Beam Tuning

- Python3 is used to develop HLA
  - Fast Linear Accelerator Modeling Engine (FLAME) of beam envelope calculation
  - pyQt5 for graphical user interface
  - Control packages (EPICS etc.)
  - Develop on Jupiter-notebook at first for proof-of-principle
- 37 applications are available on HLA Launcher
  - Operators are also use a limited number of applications for monitoring and simple tuning
- Keep upgrading to reduce tuning time
  - Measurement-based to model-based calculation

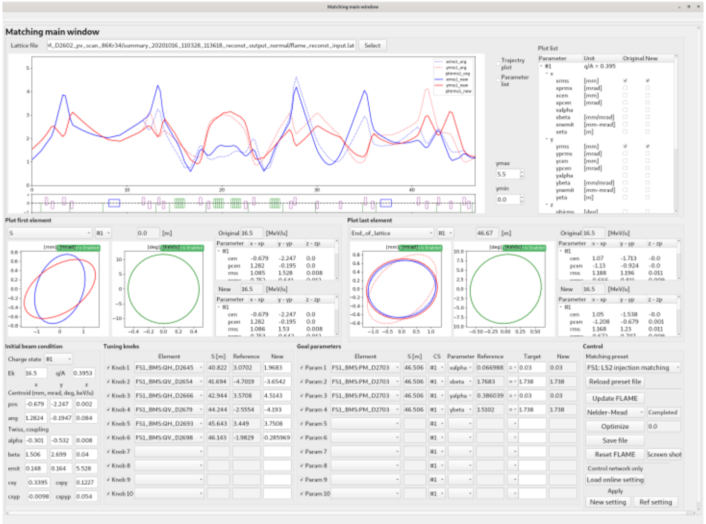


HLA Launcher

Phase scan application



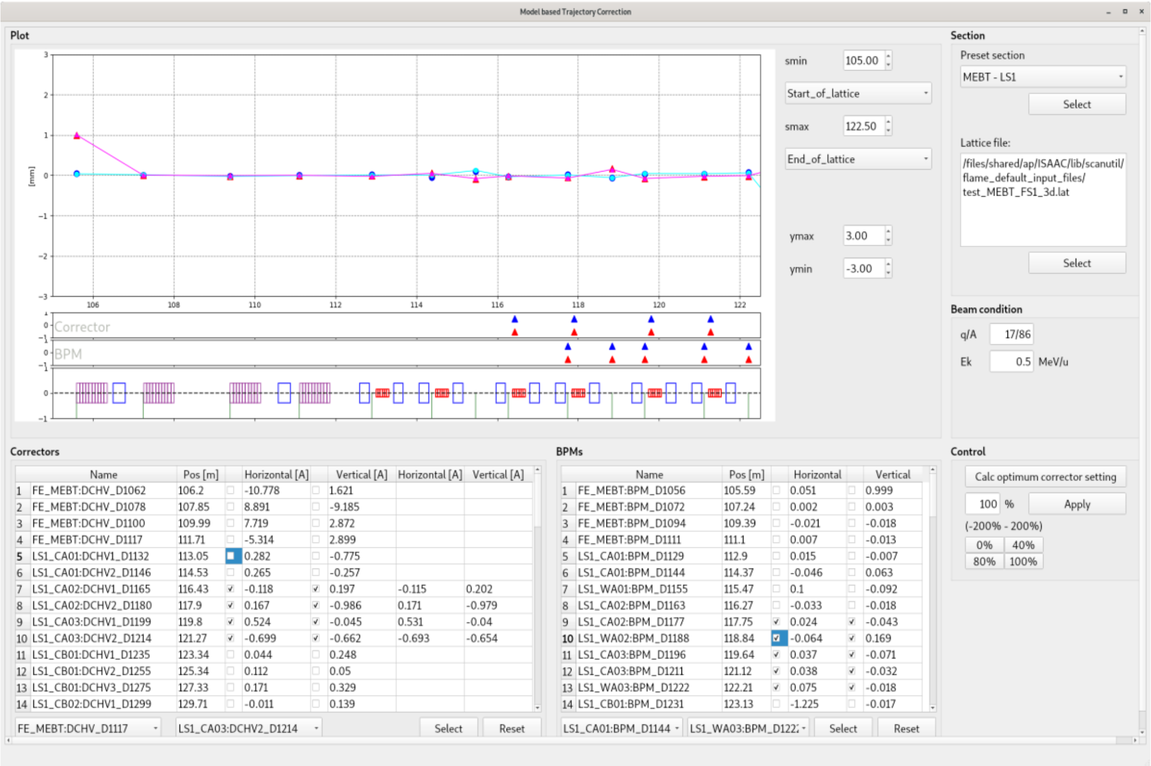
Matching application



Improvement of Trajectory Correction

Extending to Tune the Entire Segment by One Button

- Trajectory Correction application has been used since 2019
  - Orbit response matrix method with measurement-based beam response
  - Trajectory in two cryomodules of LS1 were tuned in about 30 minutes in September 2019
    - » Spent most of time to measure BPM response to upstream corrector change
    - » 6 correctors and 8 BPMs
- Implemented model-based trajectory correction application in 2021
  - Calculate response matrix by FLAME
  - Tuning for a few cryomodules in a few minutes
- This application will be upgraded to series of tuning for the entire linac section by one button

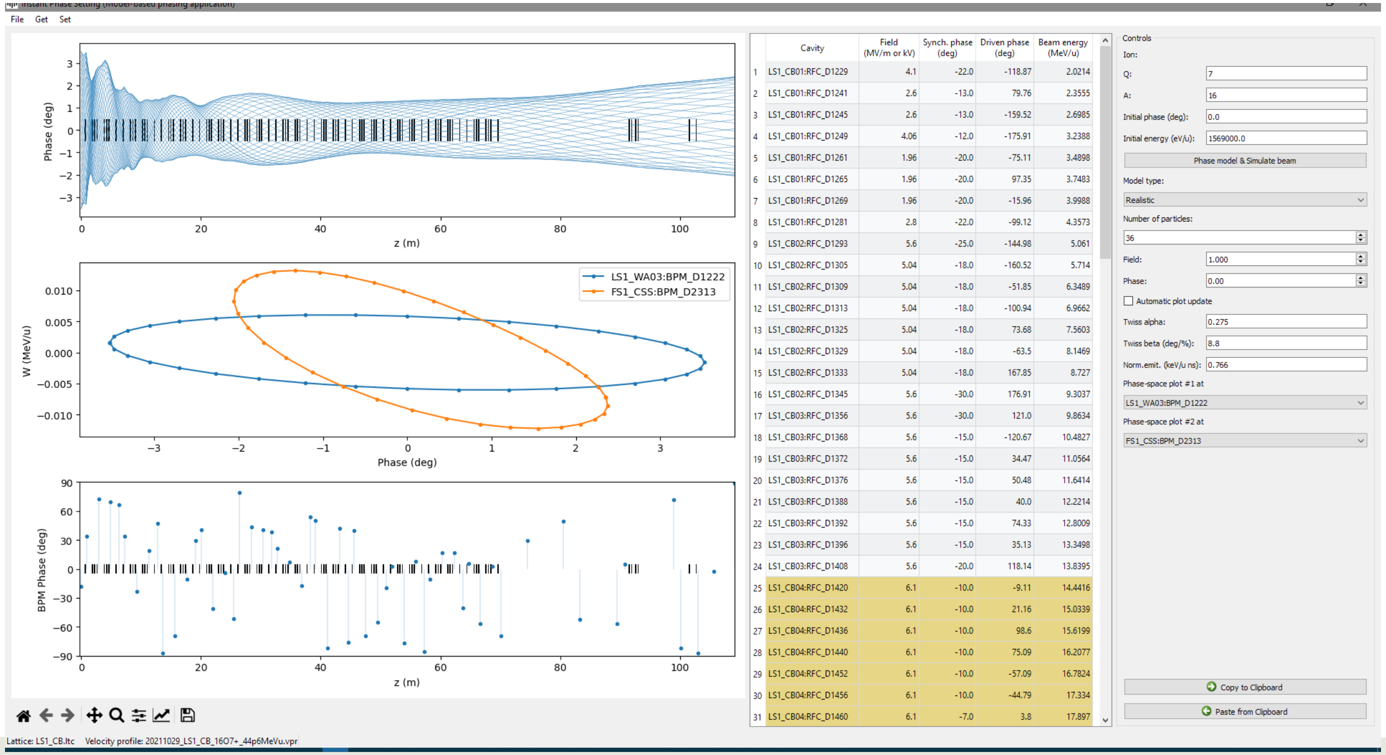


Cavity Tuning Applications

A. Plastun, NAPAC2022, THZD1

Tuning Time Reduced from Minutes per Cavity to per Section

- In 2018, the first phase scan was conducted by a Python script on Jupiter-notebook
- In October 2020, the Automated Phase Scan (APS) application was introduced for cavity tuning by means of time-of-flight measurement
  - Up to 30 superconducting cavities were automatically tuned in about 20 min in October 2020
  - However ~20 hours are necessary to complete all cavities' tuning
- In 2021, the Instant Phase Setting (IPS) application was developed for model-based calculation of cavity phase and amplitude
  - Few minutes to calculate field and phase of each linac section
  - BPM phases of APS tuned and IPS are consistent within +/-1 degree
  - Successfully developed 4 ion species with 10 different energies for FSEE operation
    - » In each setting, calculated energy after LS1 is consistent with measured energy within <+/-10 keV/u

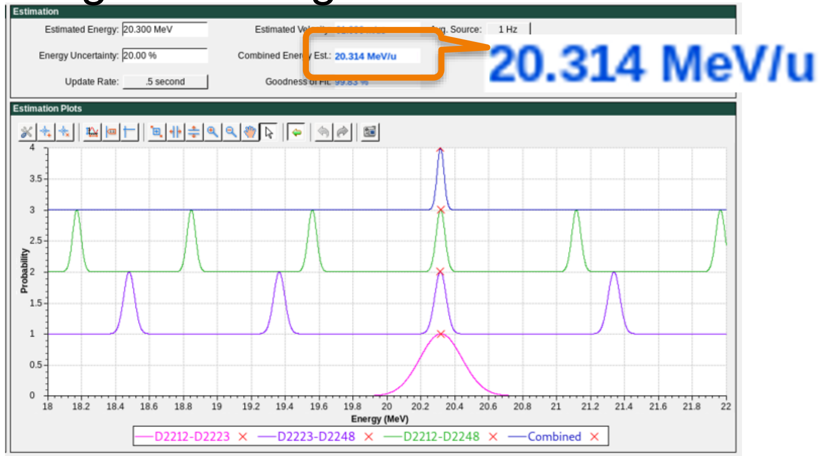


Recovery of One Cavity Failure in LS1 by IPS
Alternative Cavities' Setting Established in 10 Minutes

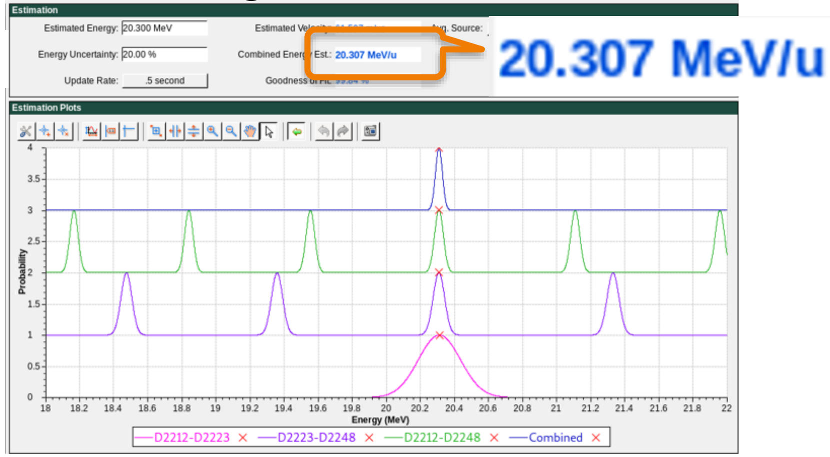
- On March 29th, one SC cavity (CB09 #8) tripped off and it was hard to restart
- Alternative cavity setting was developed by IPS so that beam energy is recovered to 20.3 MeV/u without the faulted cavity
  - Set lower synchronous phase angle in CB08 to CB11 cavities
  - Re-setting took 10′ but can be significantly reduced in future, to less than 1′
- The energy difference is only 7 keV/u

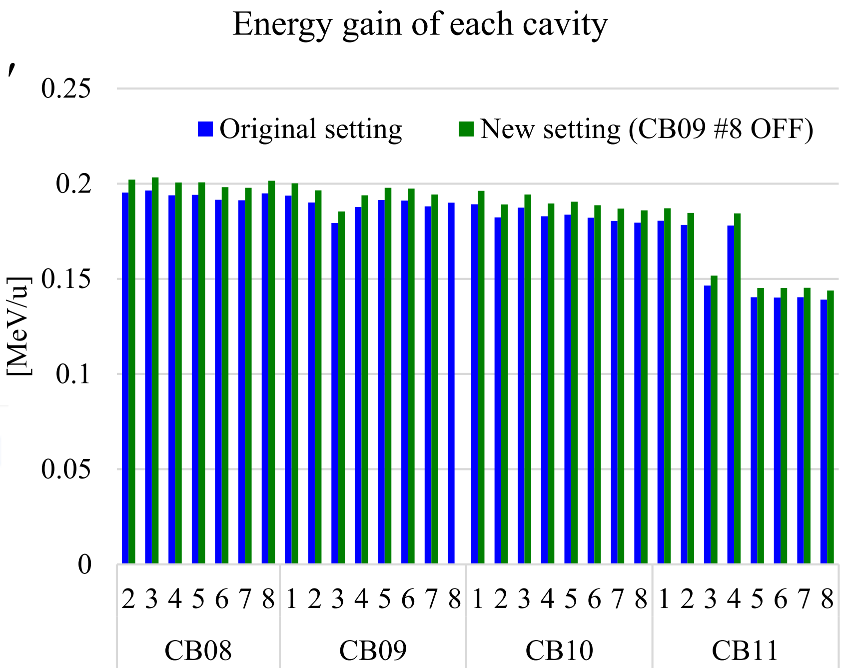
Beam energies after LS1

Original setting



New setting





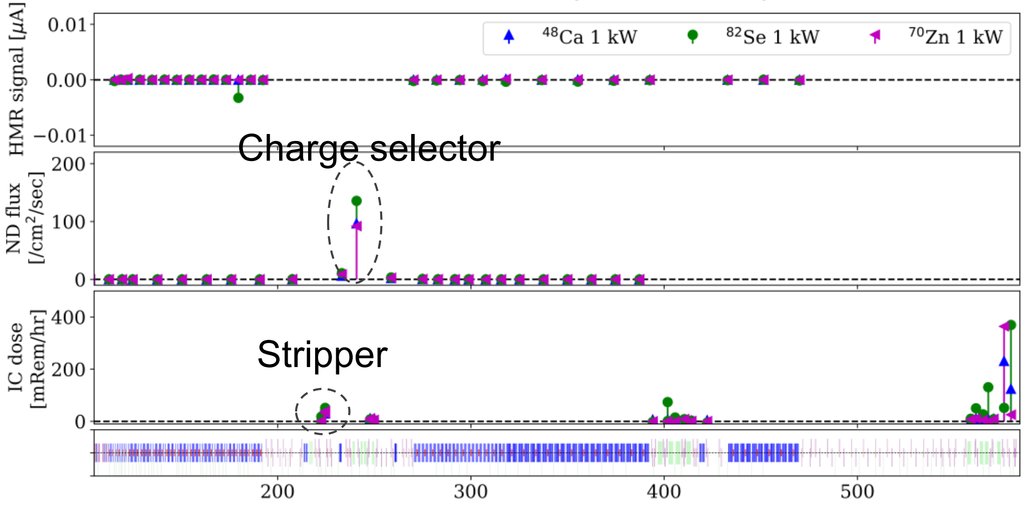
Three Experiments Successfully Completed with 1 kW Beams

- Three experiments have been successfully conducted from May to July
  - Beam time is about 10 days for each experiment
  - Rotating carbon foil is used as a stripper

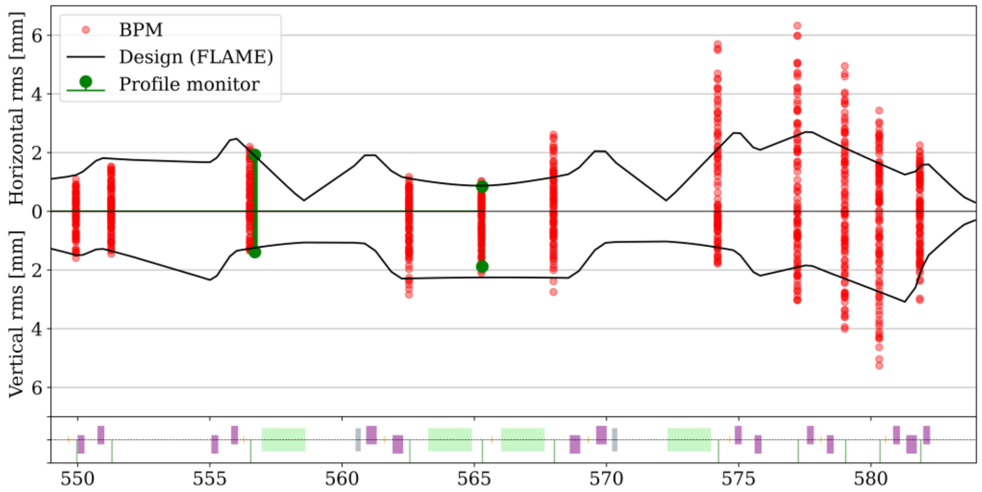
Exp #		Primary beam	Secondary beam
21062	May	^{48}Ca	^{42}Si
21069	June	^{82}Se	^{49}K and ^{52}K
21007	July	^{70}Zn	^{65}Co and ^{64}Fe

- Beam loss monitors near the target shows some signals in addition to the charge stripper and selector
- Transverse mapping measurement shows that the beam size before the target is larger than design
  - The envelope will be tuned before the next user operation

Beam loss monitor signal during 1 kW



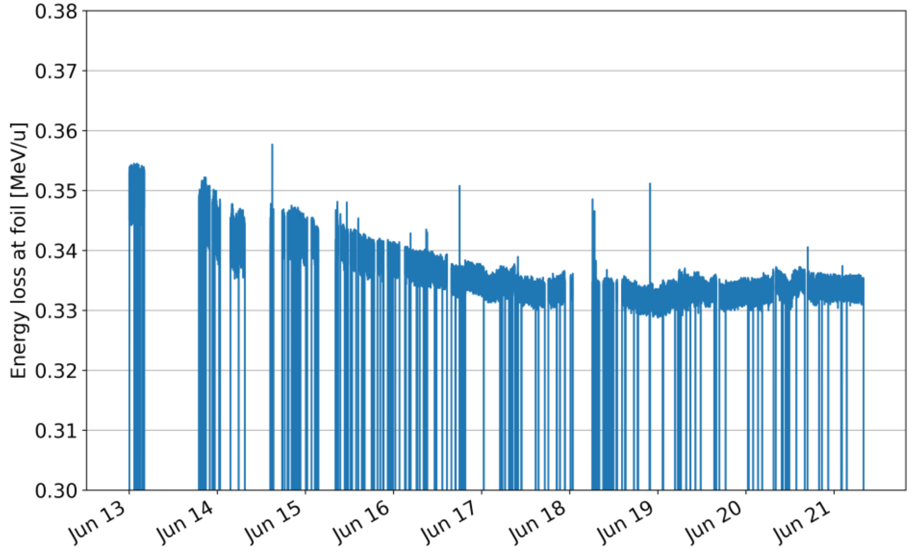
Transverse beam envelope near target

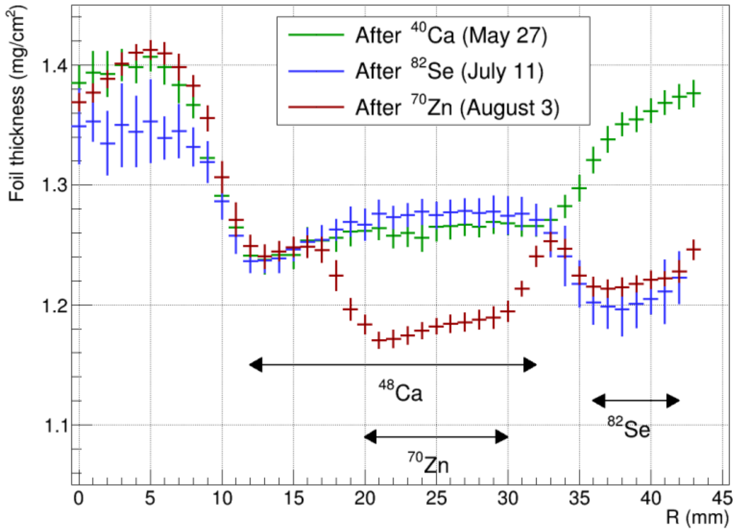


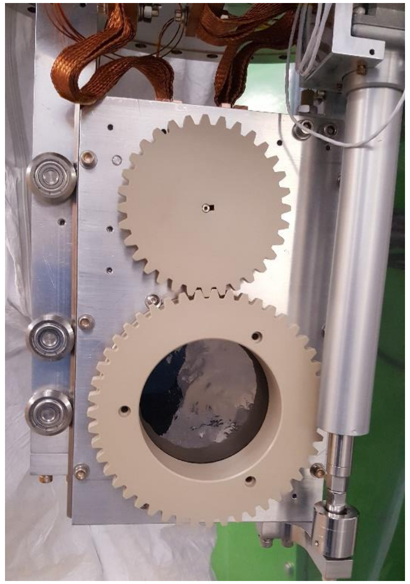
Rotating Carbon Foil Applied to 1 kW User Operations Thinning Observed

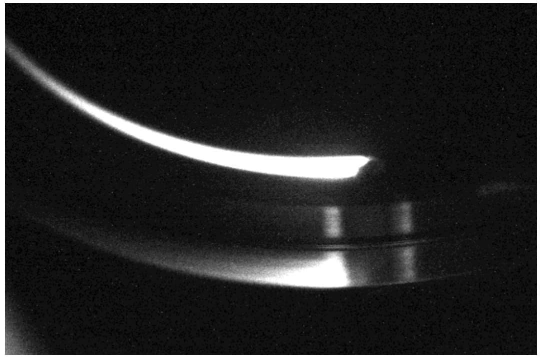
- Use rotatable carbon stripper for simplicity of operation
  - 100 mm diameter foil, rotating and up-down motion
  - One foil has been used for three experiments
- The energy loss at the carbon foil reduced by 5% during 1 kW operations
  - The foil thinning continued the first 4 days and stabilized afterwards
  - Lifetime is sufficient for an experiment with 10 kW primary beam

Foil energy loss during ^{82}Se operation







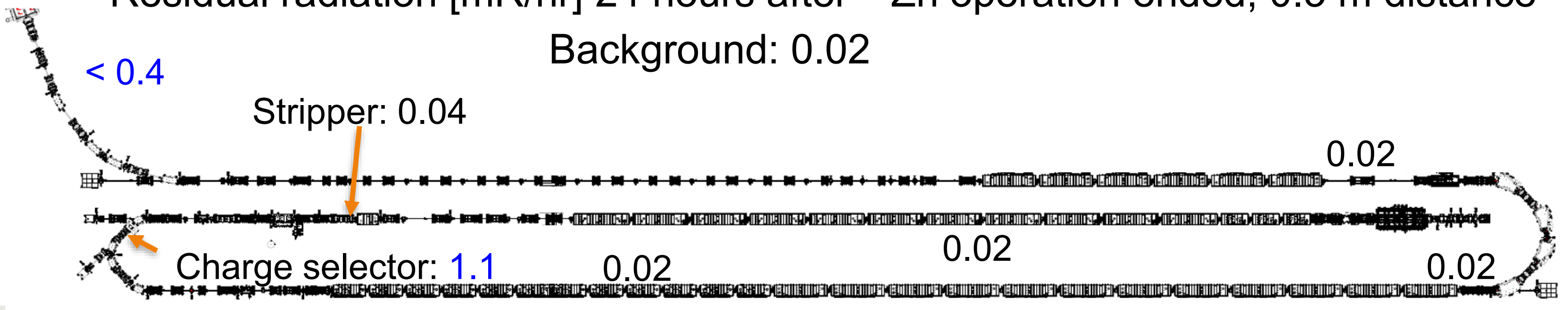


Conclusions

- Beam commissioning of the FRIB is successfully completed
  - FRIB threshold key performance parameters were met in December 2021
  - Charge stripping by liquid Lithium film was demonstrated and used in one of experiments
  - Demonstrated multi-charge state acceleration after the stripper
- High level applications have been developed to increase beamtime for science
  - 37 HLAs have been developed for efficient beam tuning
  - Upgrade from measurement-based to model-based calculations reduces tuning time
  - Beam recovered in short time without a fault cavity by IPS
- Three user experiments were conducted from May to July with 1 kW primary beams
  - No notable residual radiation has been observed except nearby of interceptive devices
  - The thickness of carbon stripper foil gradually reduced

Residual radiation [mR/hr] 24 hours after ^{70}Zn operation ended, 0.3 m distance

Background: 0.02



Acknowledgments

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